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14. ABSTRACT This research program demonstrated that flared-cup diaphragms made from polycarbonate can be shot down a smooth bore tube and that they form a tight pressure seal wherever they come to rest. Control of the stopping position was achieved by shooting the cup diaphragm with excess velocity into a tube insert that had serrated ridges formed by cutting annular grooves inside the tube walls. The combination of internal pressurization and spring tension forces pushed the walls of the cup diaphragm deeply into the grooves of the insert, which abruptly stopped the diaphragm movement and formed a good pressure seal. Live-fire ram accelerator experiments showed that projectiles with magnesium nose tips can readily penetrate the thick-walled polycarbonate diaphragms without any impact on ram accelerator performance, and that the diaphragm fragments are completely blown out of the catcher insert every time. These experimental results demonstrated that a breech-loaded diaphragm system can be readily implemented.					
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# **University of Washington**

## **Investigation of Rapid Pressurization Techniques for the Ram Accelerator**

**Final Report**  
**July 1, 2001 – December 31, 2002**

ONR Grant No: N00014-01-1-0991

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## **Research Program Summary**

Means to propel breech-loaded diaphragms through a ram accelerator launch tube in a manner that stops them at predetermined positions while enabling a gas-tight seal at fill pressures up to 2220 psi have been demonstrated. Cup-shaped polycarbonate diaphragms were launched with a small charge of pressurized nitrogen for distances of 1 and 2 meters and then stopped at the desired position with a carefully designed catcher insert. Proof-of-concept experiments were carried out which showed that projectiles with magnesium nose tips could readily penetrate the thick-walled polycarbonate diaphragms without any impact on ram accelerator performance, and that the diaphragm fragments were completely blown out of the catcher insert every time. Thus breech-loading a cartridge containing a ram accelerator projectile along with the necessary diaphragms can readily be done without the need of launch tube diaphragm changing mechanisms. Details of the hardware, procedures, and experimental results are provided in the main body of this final report.

Concurrent with the breech-loading diaphragm investigation was a study of the feasibility of utilizing solid gas generators for ram accelerator propellant storage. Several candidate gas generator technologies were identified that can be readily adapted to the task of rapidly loading a ram accelerator to very high pressures. Nitrogen and hydrogen gas generators are the most highly developed devices currently available and the potential of using fuel-rich gunpowder-like propellant formulations for generating gaseous hydrocarbon fuels appears to be quite feasible in the near term. On the other hand, conventional oxygen generator capabilities need to be significantly enhanced to meet the high pressure and rapid loading requirements. Means to cool the gases and separate particulates arising from these gas generation processes will also need to be further developed. Details of this study were originally provided in an interim report (submitted December 31, 2002) that has been attached as Appendix A.

### **1. Introduction**

The primary goal of this research program was to develop a means to eliminate the need for a diaphragm-changing mechanism at the muzzle of the ram accelerator. In addition, it is highly desirable to actually use a breech-loaded cartridge, containing the ram accelerator projectile and launch tube diaphragms, that can effectively shoot the diaphragms into their desired entrance and exit locations in a manner that enables them to seal high pressure (up to 5000 psi) gases, as shown in Fig. 1. In this scenario, the entrance and exit diaphragms are launched together with a gas generating charge stored around and/or ahead of the projectile. After the diaphragm combination reaches the entrance diaphragm stopper (or just before), a gas generating charge between the two diaphragms is ignited (initiated by timing or in-bore sensors) and the exit diaphragm continues to be pushed down the tube. The exit diaphragm is eventually stopped at the muzzle end of the ram accelerator and the residual diaphragm propellant gases are vented. The high pressure ram accelerator propellant is subsequently loaded and then the main powder charge in the breech is fired to launch the projectile and initiate the ram accelerator process. The primary result of this recently completed research program is that the launching sequence illustrated in Fig. 1 appears to be quite feasible with relatively modest modifications to existing naval cannons (e.g., the Mark-45) and would eliminate the need for having diaphragm-changing mechanisms at both the entrance and exit of the ram accelerator launch tube.

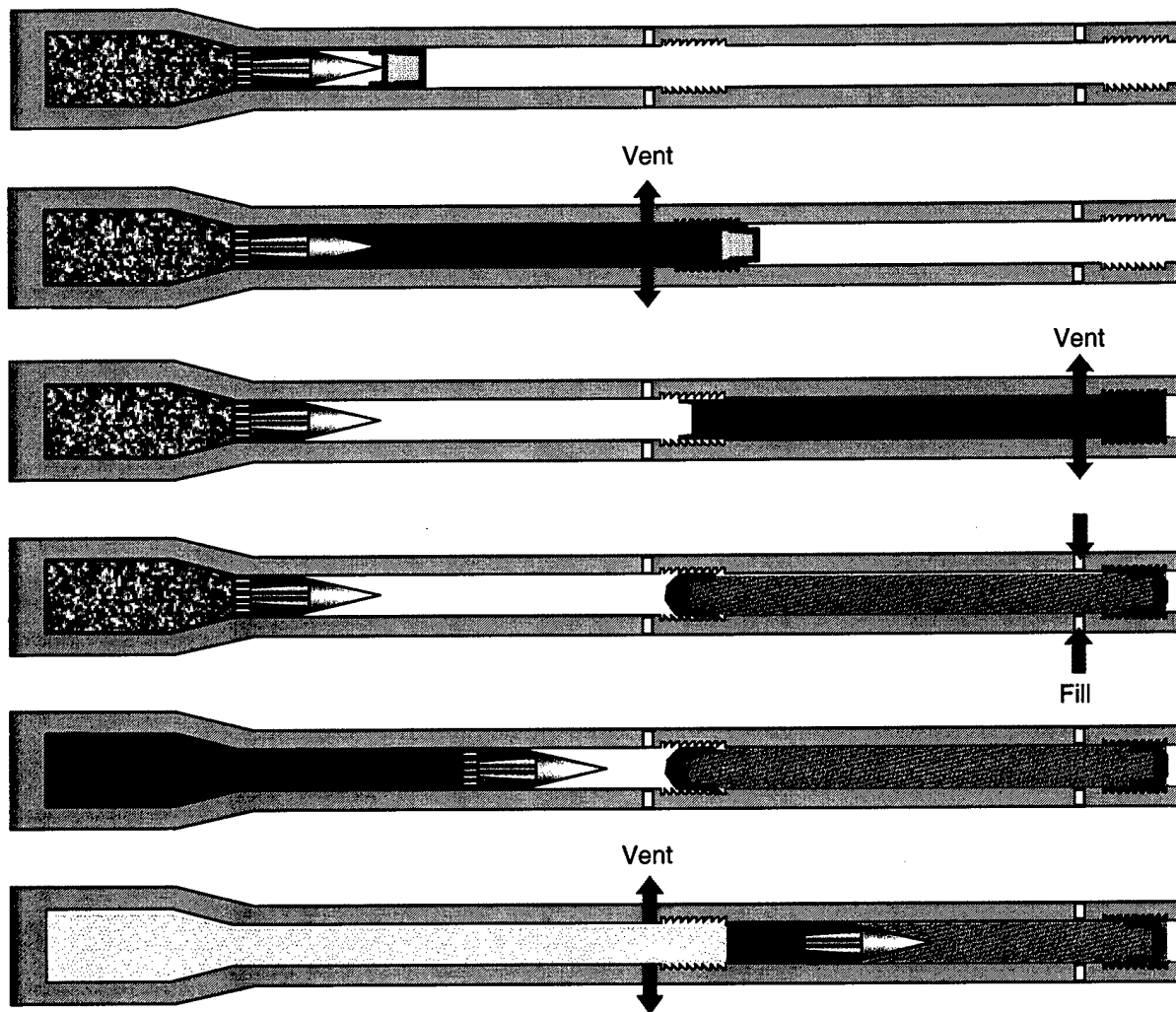


Fig. 1 Ram accelerator operating sequence with breech-loaded diaphragms.

Various means of forming effective high-pressure static seals for gaseous propellants with polycarbonate diaphragms were evaluated. The diaphragm must have sufficient axial restraint to keep the pressure from dislodging and blowing it down the tube. In addition, the pressure must act on the diaphragm in such a manner that the seal becomes more effective as the fill pressure is increased. Examples of two different static seals at the exit of the ram accelerator tube that meet these criteria are illustrated in Fig. 2. Neglecting ambient pressure, the sealing pressure ( $P_{\text{seal}}$ ) of a "Bridgeman" seal (shown in Fig. 2a) is much greater than the internal pressure ( $P_{\text{internal}}$ ); only a short section of the tube bore need be oversized to effect this kind of closure. Alternatively, the diaphragm shown in Fig. 2b is effectively a "champagne cork", i.e., the length of the flare ( $L$ ) is such that it develops a static frictional force ( $F_{\text{friction}}$ ) that will resist motion due to the axial force from internal pressurization. In principle, appropriate choices for the material, temperature, pressure, and surface condition of the diaphragm and internal tube wall will ensure that there is sufficient friction force to retain the diaphragm. The potential of combining various aspects of these closure configurations was experimentally investigated.

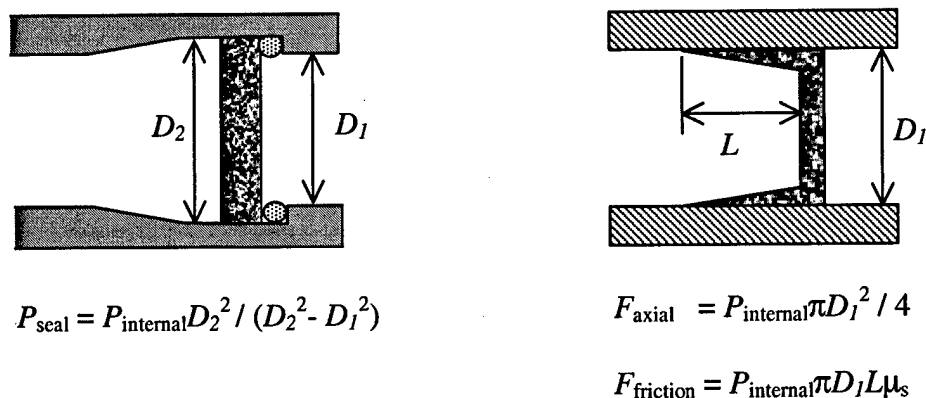


Fig. 2 Closure concepts for high pressure static seals ( $\mu_s$  is static friction coefficient).

After exploring means to contain high-pressure propellants with closures that were not restrained by being clamped between joints of the ram accelerator launch tube, the potential for launching diaphragms down-bore and stopping them where desired was investigated. The constraint on this aspect of the research was to be able to reliably stop a moving diaphragm within one tube caliber of a designated point in the tube in such a manner that a high static pressure seal is realized. Upon the successful completion of this "diaphragm stopping" task, the final phase of the research program was to actually demonstrate a live fire cycle using the diaphragm launching procedures developed to date. Ram accelerator performance, projectile damage, and various logistical issues were evaluated. Details of the experiments conducted in the course of this research program are discussed in the following.

## 2. Experimental Facility

The 38-mm-bore ram accelerator facility at the University of Washington enables experimentation at propellant fill pressures of up to 200 atm. The first 4 m of the ram accelerator test section, shown in Fig. 3, consists of two 1-m-long and one 2-m-long high-pressure tubes with an outer diameter of 152 mm. These tubes are designed for a maximum static load of 10,200 atm (150,000 psi). The remaining 12 m of the test section is comprised of six tubes, each 2 m in length with outer diameters of 102 mm, that are designed to withstand a peak static pressure of 5,500 atm (81,000 psi).

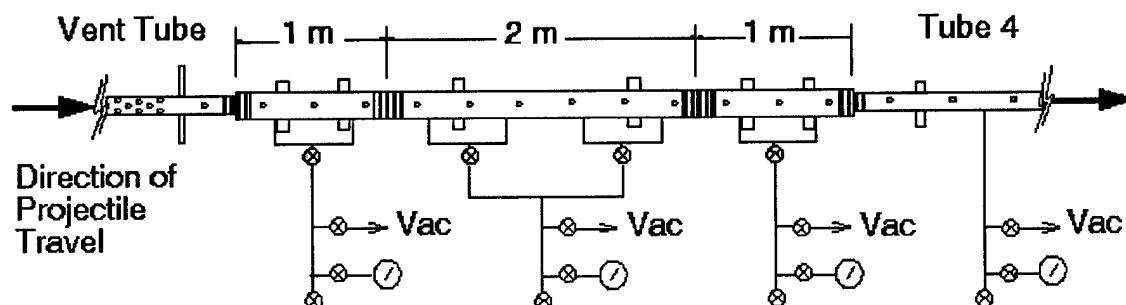


Fig. 3 High-pressure test section schematic.

The 1-m-long tubes (Fig. 3) have three instrument stations with diametrically opposed ports, whereas the 2-m-long tube has six pairs of ports. These stations are spaced along the tubes at 333 mm intervals. The first instrument station in the high-pressure section is 167 mm from the entrance diaphragm. The last station in the high-pressure tubes is spaced 167 mm from the end of the last thick-walled tube, and 396 mm from the first instrument port in the lower-pressure-rated portion of the test section. All of the instrument ports can accommodate electromagnetic (EM) probes and piezoelectric pressure transducers.

### 3. Experimental Procedures and Results

The experimental program was carried out in several distinct phases in which the configuration of the ram accelerator test section was significantly altered. The progression of testing went from static pressure sealing concepts, to dynamic launching, controlled stopping, and finally to live-fire proof-of-concept demonstrations. The primary goal of the static tests was to determine a means to effect a reasonably tight gas seal at pressures up to 2000 psi, without having to mechanically clamp a diaphragm between tube joints. In the controlled stopping experiments, the goal was to stop the diaphragm within one tube caliber of the desired position, while still maintaining the gas tight seal. Live-fire ram accelerator experiments were conducted to investigate logistical issues associated with the diaphragm launching cycle. The procedures and results of each of these phases of testing are described in the following subsections.

#### 3.1 Static pressure tests with straight-walled diaphragms

Initial static pressure sealing tests were carried out with straight-walled polycarbonate "cup" diaphragms like that shown in Fig. 4. The variables investigated were the wall thickness, face thickness, and length-to-diameter ratio. The cup diaphragms were placed at the entrance of a 2-m-long launch tube and a tube insert was installed at the same joint to enable the pressurization

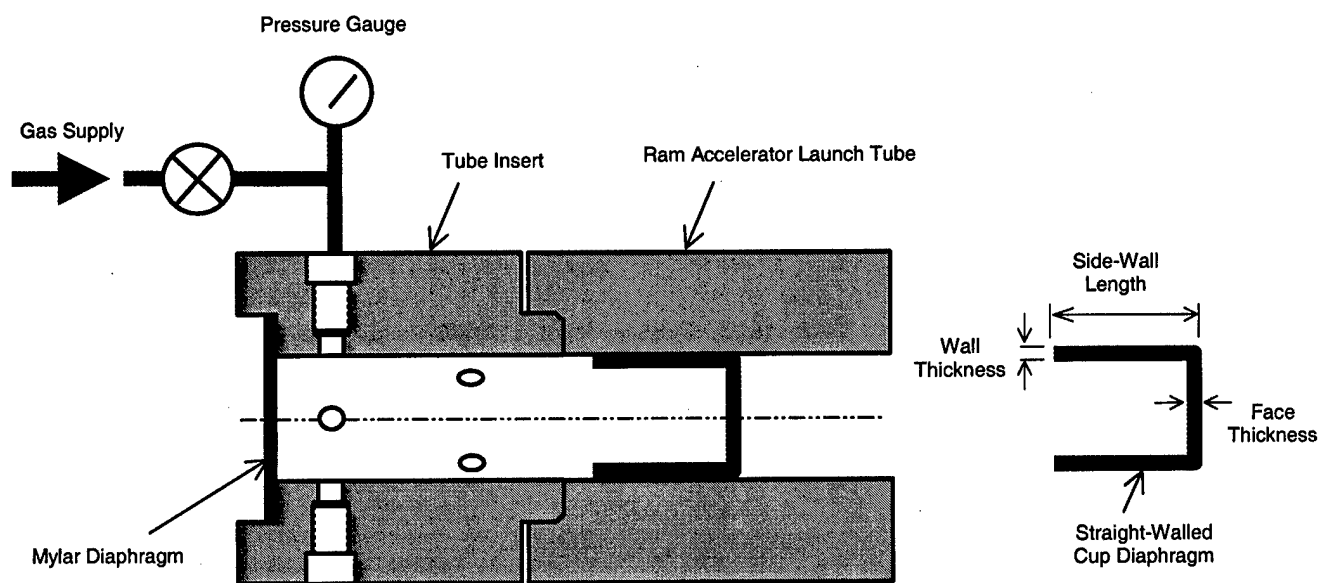


Fig. 4 Insert configuration for static pressure tests with straight-walled diaphragms.

tests with relatively small quantities of gas. Cylinders of  $N_2$  were used to pressurize the volume between the cup diaphragm and Mylar end-wall diaphragm and the leak rates (if any) were determined. The results of these tests showed that under no circumstances were the cup-shaped diaphragms able to hold several hundred psi without leaking. On the other hand, if the insert volume was rapidly pressurized the cup would abruptly move 10-30 cm down bore and stop, but it still could not maintain a satisfactory static pressure seal. It was hypothesized that the gas leaking around the diaphragm kept the pressure differential too low for the Bridgeman effect to be realized. It may have been possible to achieve a good pressure seal using a straight-walled cup diaphragm that had an interference fit with the tube bore; however, since this possibility would not lead to any simplification in field applications, it was not pursued.

### 3.2 Static pressure tests with conical insert

In order to realize a better static pressure seal, a conical-bore tube insert was fabricated to hold flared-cup diaphragms as shown in Fig. 5. This approach combined the essential elements of the two closure concepts shown in Fig. 2; i.e., the slightly larger-bore section of tube provided enhanced resistance to axial motion and the flared walls enabled the internal pressurization to fully press the side walls of flared-cup diaphragms against the inside surface of the coned insert. The insert was coned with a  $5.5^\circ$  half angle and its length was 33 mm. This angle and length were chosen to provide enough projected frontal area for the conical-bore tube insert to restrain a polycarbonate cone frustum without it shearing when pressures of up to 3000 psi were applied. A stack of 8-10 Mylar diaphragms was placed behind the instrumented insert to enable static tests to be carried out at high pressure.

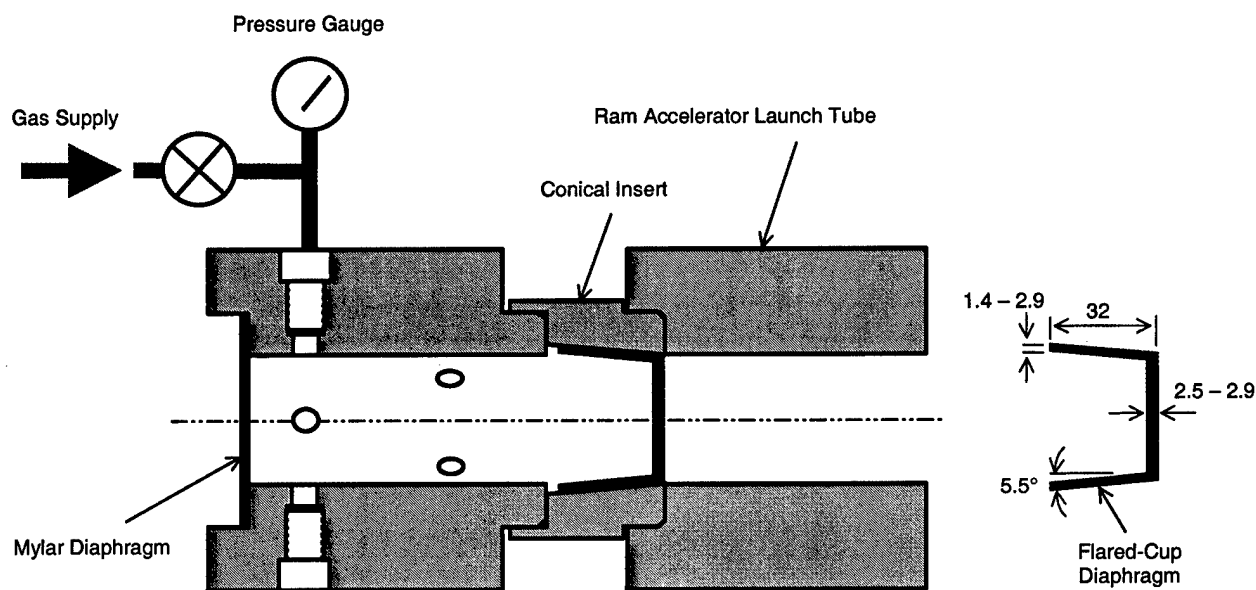
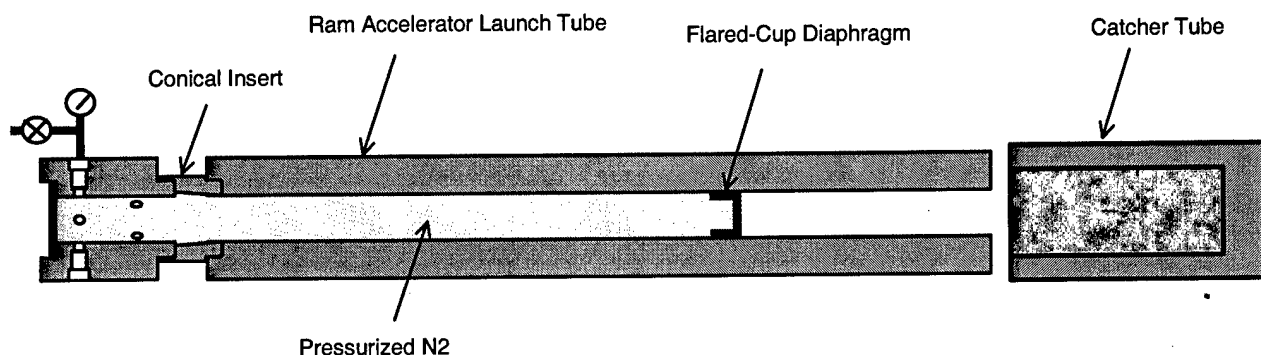


Fig. 5 Insert configuration for static pressure tests with conical diaphragm holder (dimensions in millimeters).



**Fig. 6 Static pressure tests for flared-cup diaphragms launched from conical insert.**

The sealing capabilities of various geometries of flared-cup polycarbonate diaphragms in the conical insert were investigated. The overall length of the cup diaphragms for this particular series of tests was kept at 32 mm, whereas the wall thickness was varied from 1.4-2.9 mm and the face thickness varied from 2.5-2.9 mm. The insert chamber volume was slowly pressurized with N<sub>2</sub>. At various pressure levels, the gas supply was shut off and the seal effectiveness was ascertained by timing the resulting rate of decrease in pressure. Ultimately, the pressure in the insert chamber volume would reach the point where the cup diaphragm would suddenly shoot down the bore. The diaphragm would then come to rest somewhere in the smooth bore launch tube and form a very tight pressure seal, as illustrated in Fig. 6. The residual gas behind the cup was vented and its position from the exit of the launch tube was then measured. The volume behind the cup was re-pressurized and the new static seal was leak-tested. Ultimately, either the face of the cup blew off or else the whole cup was shot completely out of the 2-m-long launch tube. A short tube with a relatively large inner diameter (76 mm I.D.), packed with rug remnants, was placed at the end of the launch tube segment to catch the diaphragm debris.

The experiments with the conical insert and flared-cup diaphragms were very successful. The static seal in the conical insert held pressures up to 1550 psi without any leakage in this phase of the testing. The thicker the walls of the flared-cup diaphragm, the greater the insert chamber pressure had to be before the cup began moving. On the other hand, if the wall thickness was too great (e.g., 2.9 mm in these experiments), a satisfactory pressure seal in the insert could not be realized; which implied that the flared walls of the cup were too rigid. The ability of the conical insert to hold a conical diaphragm and maintain a gas-tight seal without mechanical clamping suggests that a dynamic closure system could be feasible in which flared-cups are shot down-bore to a station with a coned insert.

The results of the static pressure tests on the flared cups that had stopped in the smooth bore launch tube were very enlightening. It was found that these cups were firmly seated in the tube and that they held from 10% to 80% more pressure than that required for launching them out of the conical insert. Generally, the thinner the walls of the cup, the farther down bore it would travel before stopping. The subsequent "burst" pressure in the smooth bore tube also decreased with thinner walls. Even though the 2.9 mm-thick-walled cup diaphragms did not have an adequate pressure seal in the conical insert, they maintained an excellent static pressure seal up to ~2200 psi after being launched into the smooth bore launch tube, whereas the 2.54-mm-walled



cups held only ~900 psi after being launched. The tightness of these static seals in the smooth bore tube were so impressive that the research efforts were immediately redirected toward developing a means to reliably stop the diaphragms in a smooth bore tube at any designated point.

### 3.3 Diaphragm launching tests with mini gas gun

The variability of the stopping distance of the flared-cup diaphragms was found to be too large ( $\pm 20$  calibers) in the preliminary tests with the conical insert (Sec. 3.2). This was attributed, in part, to the variability of the pressure at which the cup begins to move. Thus, a means of releasing a controlled quantity of pressurized gas behind the cup was devised. Existing tube inserts were stacked together in a manner that created a breech chamber volume of ~87 cc and an inter-diaphragm volume of ~35 cc, as shown in Fig. 7. A thick end-wall diaphragm, composed of a stack of ten Mylar diaphragms (14 mil thick), was used to seal the rear of the breech of the mini gas gun. Combinations of 2 or 3 Mylar diaphragms were used at the breech and inter-diaphragm locations as needed for the desired launch pressure. The instrument holes in the inserts were plumbed to allow evacuation, pressurization, and pressure monitoring via the existing gas handling system. The gas fill line for the breech chamber volume was isolated from the inter-diaphragm section with a ball valve. The flared-cup polycarbonate diaphragm to be tested was placed in the conical insert at the entrance to the launch tube.

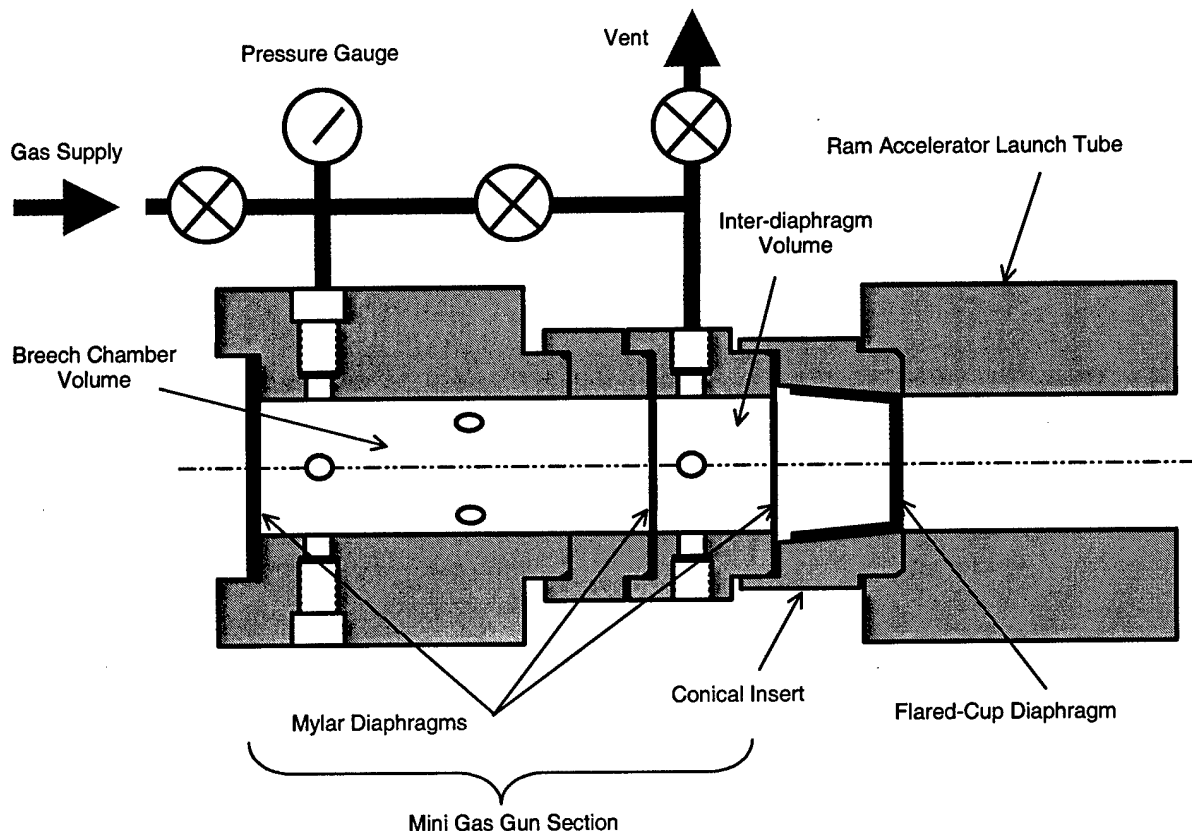


Fig. 7 Insert configuration of mini-gas-gun used for dynamic launch tests of conical diaphragms.

Experiments were carried out with the breech chamber volume pressurized with  $N_2$  anywhere from 1500 to 2220 psi with the inter-diaphragm volume filled to approximately half the breech pressure. The vent valve to the inter-diaphragm volume was then opened to shoot the cup diaphragm down a test section that was comprised of two 2-m-long tubes. The diaphragm debris catcher tube was moved to the exit of the second 2-m-long tube. The resting position of the cup was measured and the new pressure seal was evaluated by pressurizing the total volume behind the diaphragm. The static pressure seals in the smooth bore tubes were excellent during these tests.

Ultimately, it was determined that the cup diaphragms having wall and face thickness of 2.8 mm and 2.9 mm, respectively, could not be reliably stopped just beyond the exit of the first 2-m-long launch tube. A few attempts were made to vent the mini gas gun gases just as the cup diaphragm entered the second tube. The venting was accomplished by leaving a 13 mm gap between the two tubes. The venting helped but the variability of the stopping distance ( $\pm 7$  calibers) was still not adequate for the purposes of this research program. These results indicated that an external means to stop the diaphragms would be necessary.

### 3.4 Diaphragm-stopper inserts

Since the prior experiments had shown that rapid venting of the gas behind the moving cup diaphragm was insufficient to control its stopping point, means to abruptly halt the motion of the cup using alterations to the internal tube wall shape were explored. An approach that proved to be quite effective relied on the combination of internal pressurization and spring tension forces of the constricted flared-cup diaphragms to interact with annular ridges formed by machining recesses into the tube wall. To test this concept, tube inserts were manufactured with internal serrations to stop the movement of the diaphragms. The first prototype was fabricated from an old launch tube end, as shown in Fig. 8. Annular grooves were cut inside at a spacing of 6.4 mm, and the resulting ridges were 3.2 mm high. These annular ridges were machined with a "buttress thread" like shape and the overall length of the serrated region was  $\sim 2$  calibers ( $\sim 8$  cm). This tube insert was held to the end of a 2-m-long launch tube by a threaded collar and placed in front of the debris catcher tube filled with rug remnants as shown in Fig. 9.

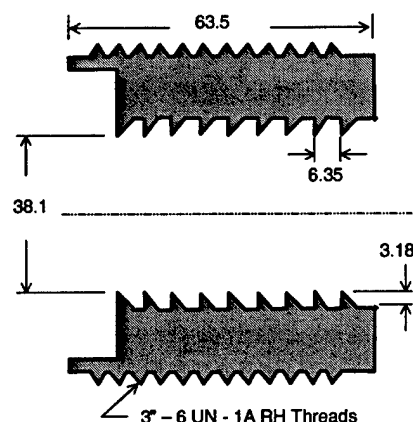
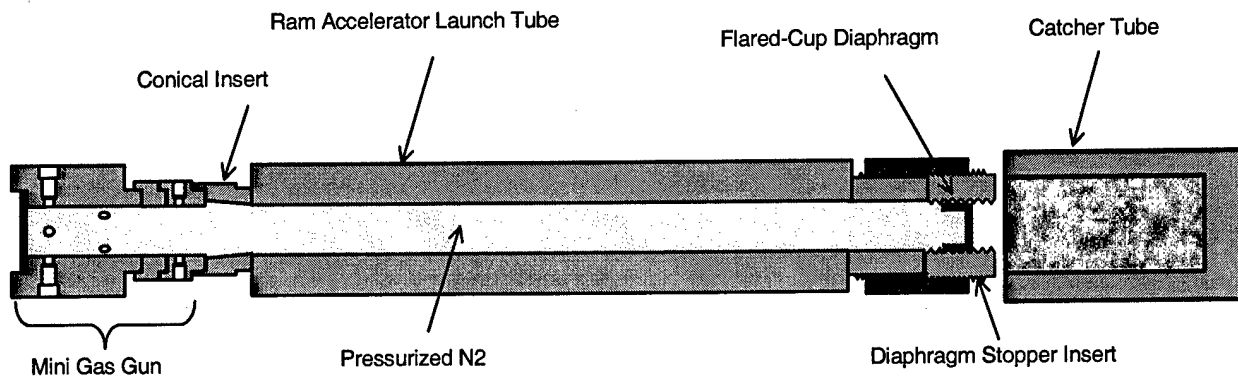


Fig. 8 Prototype of cup-diaphragm stopper insert (dimensions in millimeters).

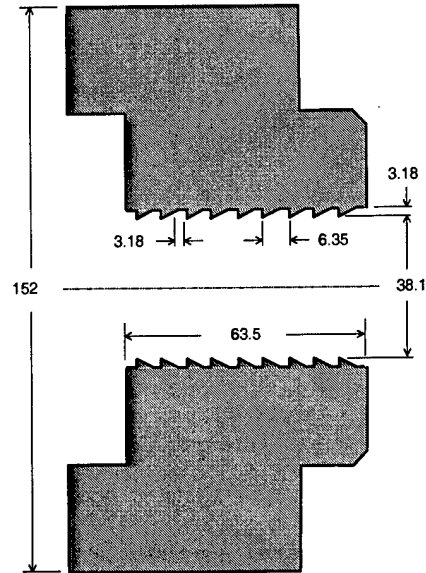


**Fig. 9 Testing configuration of prototype diaphragm stopper insert with 2-m-long launch tube.**

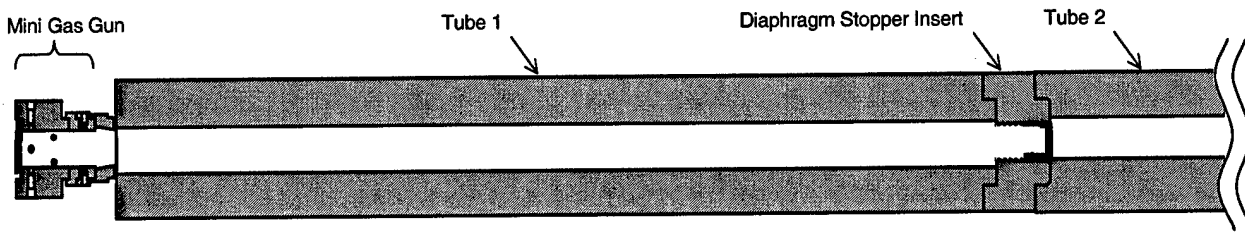
The first set of experiments showed that the insert would reliably stop flared-cup diaphragms having 2.9 mm thick face and 32 mm-long side walls that were 2.5 mm thick. Once the diaphragms were stopped in the insert, they would maintain a high quality static pressure seal up to the point where their faces burst (1280 – 1450 psi). In attempts to reduce the side wall length it was found that shorter cups (17 mm-long side walls) would blow right through the insert without stopping. Thus, a minimum length of flared-wall on the cup diaphragm was needed for it to be caught with this insert design.

Having established a means to launch and stop diaphragms at will, a new stopper insert was machined that would fit between the joints of the thick-walled (152 O.D.) launch tubes. The original design of this insert had a ridge spacing of 1.6 mm; however, this gap proved to be insufficient to reliably stop the moving diaphragms. The insert was subsequently modified to remove every other ridge leaving the geometry shown in Fig. 10. The length of serrated region was 64 mm and the ridges were spaced at 6.4 mm. The grooves were 3.2 mm deep and the annular ridges were shaped as before. The insert was placed at the end of the 2-m-long launch tube and it was found that moderately shortened (28 mm long) cup diaphragms with a slightly thicker face (3.1 mm) could be reliably stopped. These diaphragms had a good pressure seal and burst at ~1650 psi.

After demonstrating that the new insert worked with the 2-m testing configuration, the mini gas gun and 152 mm O.D. stopper insert were moved to the first 1-m-long launch tube at the entrance to the test section, as shown in Fig. 11. The insert could now be installed between the launch tubes and the system pressurized with combustible propellant. The launch dynamics of the cup diaphragms were recalibrated for the 1-m-long launch tube. This experimental configuration proved to be 100% reliable in stopping cup diaphragms that had a length of 28 mm, wall thickness of 2.4 mm, and face thickness of 2.9 mm. In the course of these experiments, it was also found that cups could be launched more reliably without bursting in the conical insert if no Mylar inter-diaphragm was used between the cup and breech diaphragm. This simplified the experimental procedure because only one set of Mylar diaphragms needed to be replaced between tests.



**Fig. 10 Diaphragm stopper insert for 152 mm O.D. launch tubes (dimensions in millimeters).**

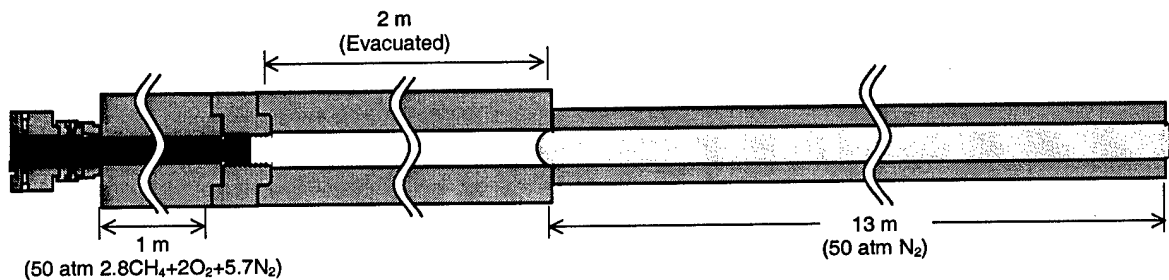


**Fig. 11 Testing configuration of diaphragm stopper insert with 1-m-long launch tube.**

### 3.5 Ram accelerator experiments using flared-cup diaphragms

Live-fire ram accelerator experiments were carried out to demonstrate the efficacy of the flared-cup diaphragm launch cycle and to investigate potential logistical issues. The launching of the cup-diaphragms leaves Mylar diaphragm fragments between the inserts of the mini gas gun, located at the entrance to the ram accelerator test section, which may have a negative impact on the starting process. After the cup diaphragm comes to a stop, there is ~350 psi residual  $N_2$  in the 1-m-long launch tube. This gas is vented to atmosphere leaving a 1 atm of  $N_2$  in the launch tube which may not mix thoroughly with propellant during its loading procedure. Finally, the penetration of the relatively thick-faced polycarbonate diaphragm could significantly damage the nose tip of the projectile and/or the leading edges of the fins. These were some of the key questions addressed during this phase of the research program.

The test section was partitioned into three different segments in order to examine the ram accelerator operating characteristics and then recover the projectile after it has pierced the polycarbonate diaphragm in a means that did not further degrade the nose tip. The mini gas gun and diaphragm stopper insert were installed at the entrance and exit, respectively, of the first launch tube, as shown in Fig. 12. The following 2-m-long tube was evacuated and the remaining 13 m of the test section was filled with  $N_2$  to 50 atm.



**Fig. 12 Ram accelerator apparatus with 13-m-long gas dynamic decelerator section.**

The most effective process for aerodynamically decelerating a sub-projectile in a short length of tube is to have it unstart and drive a normal shock ahead of it. After being ram-accelerated for a distance of 1 meter, however, the projectile is traveling at a Mach number of  $\sim 4$  relative to room temperature  $N_2$ ; this is much too fast for it too immediately unstart (Mach  $< 2.5$  is required for typical ram accelerator projectile geometries to unstart in diatomic gases). A high sound speed gas (e.g., He or  $H_2$ ) could be used to unstart and decelerate the projectile; however, the density of these gases at relatively moderate pressure (i.e., 50 atm) is too low for them to completely decelerate the projectile within a 15-m-long tube. Alternatively, an evacuated tube segment allows the ram accelerator propellant gases to expand ahead of the projectile after it penetrates the exit diaphragm. This has been found to be an effective means to insure that the projectile immediately unstarts upon its entry into an adjacent tube containing relatively dense inert gas (e.g.,  $CO_2$  or  $N_2$ ). This approach was very successful in gas-dynamically stopping the projectiles and enabled close inspection of their nose tips after they had penetrated the cup diaphragm. A "thick" (3.6 mm) diaphragm was required at the exit of the last section to reflect the unstart shock without bursting.

The projectiles for these tests were manufactured from magnesium alloy in the one-piece configuration shown in Fig. 13. Only one meter of the test section was used because this is a sufficient length to determine whether or not the projectile will start at fill pressures of 50 atm, and it is not long enough for the projectile to be significantly eroded before it impacts the polycarbonate cup diaphragm. The propellant composition was nominally  $2.8CH_4+2O_2+5.7N_2$ . The pressure field and time-of-passage data were monitored by the piezoelectric transducers and EM sensors, respectively.

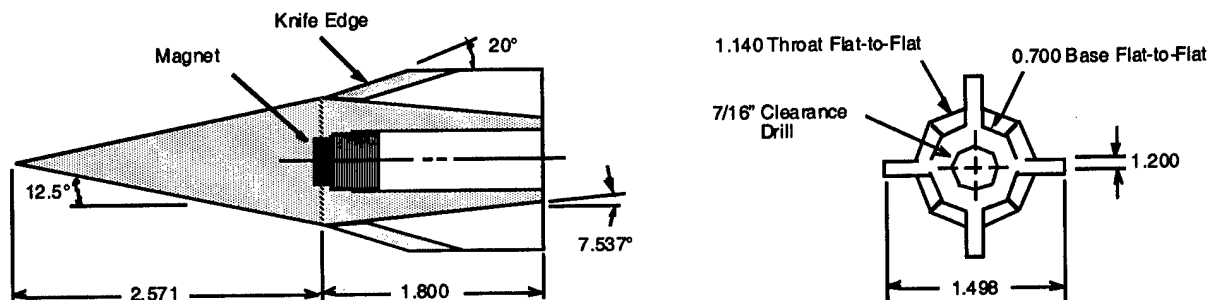


Fig. 13 Ram accelerator projectile configuration (dimensions in inches).

The purpose of the first experiment (HS1638) was to establish that the diaphragm fragments in the mini gas gun and the residual  $N_2$  from the diaphragm launching procedure did not interfere with the starting process. It was also a preliminary test of the gas dynamic projectile deceleration technique. After the cup diaphragm was launched and caught in the stopper insert, the insert was removed from the test section and replaced with standard Mylar diaphragms. The 1-m-long tube of the test section was then evacuated and refilled with pure  $N_2$  to atmospheric pressure in order to simulate the same initial conditions that follow from the cup launching sequence after the step for venting the excess diaphragm propellant gas (see Fig. 1). The tube was pressurized with propellant and the projectile was shot into it at  $\sim 1200$  m/s. The projectile successfully started and was ram accelerated for 1 m. It subsequently was caught in the gas dynamic decelerator section. This provided a good look at a projectile that had not penetrated the polycarbonate cup diaphragm, as evident by the photograph in Fig. 14.

Two shots were then carried out with cup diaphragms that had been shot into the stopper insert. In both cases the projectile was successfully started and impacted the cup diaphragm at a velocity of  $\sim 1400$  m/s. The cup diaphragm fragments were completely blown out of the stopper insert every time, thus no maintenance of the insert was required between experiments. In the first of these experiments (HS1639), the projectile was caught in the decelerator section (photograph in Fig. 14); however, in the following one (HS1640) the projectile went completely through the gas dynamic decelerator section. The failure of this projectile to be caught was attributed to the pre-bursting of the previously stressed exit diaphragm by the unstart shock wave, which allowed the helium propellant from the light gas gun initial launcher to blow everything out of the ram accelerator test section.

In the final experiment of the research program an attempt was made to start the ram accelerator with the polycarbonate cup diaphragm at the entrance to the test section. The cup diaphragm was launched as usual and was caught by the stopper insert. The mini gas gun apparatus was then removed and the stopper insert (with cup diaphragm) was installed in its place at the entrance to the ram accelerator test section. This was the first time that a pressure check was carried out with the flared-walls of the cup not being pressurized. The seal was found to be very poor in this configuration; i.e., the leak rate was  $\sim 5$  atm per minute for the 1-m-long test section. Under normal circumstances this level of leak rate would be sufficient cause to abort the experiment; however, there was such a high amount of interest in establishing that the ram accelerator could be started with a cup diaphragm at the entrance that an attempt was made anyway. Unfortunately, this experiment was not successful in starting the ram accelerator, although the projectile was recovered in the decelerator section (photograph in Fig. 14) and the

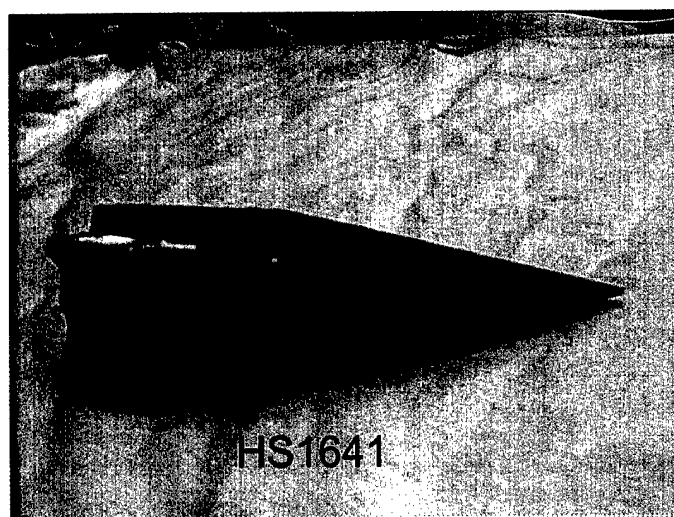
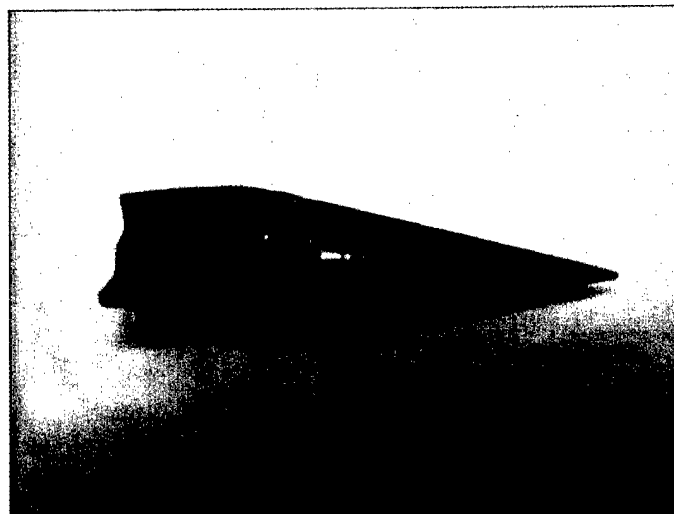
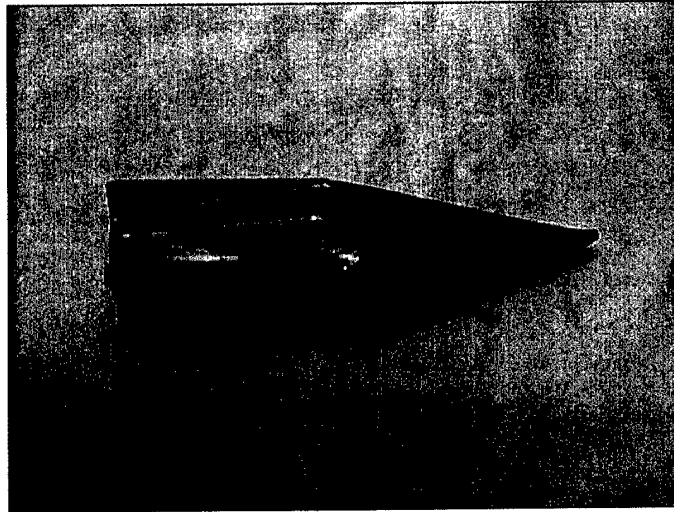
diaphragm fragments were again blown completely out of the insert. This failure to start is attributed mostly to the propellant leaking into the evacuated section ahead of the entrance diaphragm. No more attempts to start the ram accelerator in this configuration were made.

Photographs of three projectiles that were caught in the decelerator section are shown in Fig. 14. It is evident that the tips of the nose cones on the 2 projectiles (HS1639 and HS1641) that passed through the polycarbonate cup diaphragms having a face thickness of 2.9 mm were minimally affected, if at all. Perversely, some distortion is evident in the nose tip of the projectile (HS1638) that passed through a 2.1 mm thick Mylar exit diaphragm prior to being caught. Although the gas dynamic deceleration technique does not eliminate fin erosion due to tube-wall friction, it appears that the magnesium fins were not severely damaged by the penetration of the polycarbonate cup diaphragms at high speed (1200 and 1400 m/s). Indeed, the blunting of the leading edges of the fins looks to be mostly that of being exposed to supersonic flow in reactive propellants. Thus, it seems very likely that a large-scale projectile fabricated from materials that are more durable would readily pass through cup diaphragms without any detrimental effects.

#### 4. Discussion

In the course of this research program, the principle of launching cup diaphragms with a small charge of pressurized gas down a ram accelerator tube and stopping them in a serrated section was well established. Even though the concept was only demonstrated in one- and two-meter-long tubes, it is reasonable to expect that the same approach would work for distances greater than 5 m. It would be relatively straightforward to design a rapid-fire, high-velocity launch system with a diaphragm changing mechanism at the entrance to the ram accelerator section. In this scenario, the projectile and ram accelerator diaphragm cartridges could be loaded simultaneously. The exit diaphragm is shot to the end of the ram tube and the base of its cartridge is used for the entrance diaphragm. This approach eliminates the need for a diaphragm changing mechanism at the muzzle end of the launcher and provides a good entrance diaphragm that can readily seal the high pressure ram accelerator propellant. Although adding a cartridge insertion mechanism at the entrance to the ram accelerator is not as elegant as the completely breech-loaded operating scenario, it does get around the technical issue of having a stopper section at the entrance to the ram accelerator that has to let the exit diaphragm pass through it while still being able stop the entrance diaphragm.

The sealing ability of the flared-cup diaphragms was superb; however, the means by which they actually achieve this seal is not due purely to the Bridgeman effect. It turns out that the compression of the flared walls into the circular bore during the shooting process results in an outward force exerted by the cup diaphragm equivalent to several thousand psi of internal pressurization for the dimensions and materials used in this investigation. Thus, the malleable plastic is swaged tightly into the serrated ridges of the stopper segment even before the propellant is loaded. This implies that it may be possible to restrain the outward expansion of the walls of the exit diaphragm until after it has passed through the entrance diaphragm stopper segment via a timing mechanism onboard the exit diaphragm or an external signal. For example, a coiled spring can be embedded in the walls of a plastic exit diaphragm that is triggered after it has passed through the entrance diaphragm stopper section to expand and press the side walls of the exit cup diaphragm to the smooth bore ram accelerator tube. The combination of internal



**Fig. 14 Photographs of gas dynamically decelerated magnesium projectiles.**



pressurization from propellant gases and spring tension forces will insure the diaphragm is caught at the exit diaphragm stopper to the ram accelerator. This is one of several potential means to realize a breech-loaded diaphragm launching system.

The fact that the diaphragm fragments were blown completely out of the serrated stopper insert is a fortuitous discovery. It was not known prior to the live-fire ram accelerator experiments what sort of residues would be left in the stopper, and if a means to rapidly clean it out would need to be devised. It appears, however, that the projectile passage breaks up the diaphragm remnants sufficiently for the propellant gases to sweep them out of the system. This greatly simplifies the design a rapid-fire ram accelerator launcher.

## **5. Conclusions**

This research program demonstrated that flared-cup diaphragms made from polycarbonate can be shot down a smooth bore tube and that they form a tight pressure seal wherever they come to rest. Control of the stopping position was achieved by shooting the cup diaphragm with excess velocity into a tube insert that had serrated ridges formed by cutting annular grooves inside the tube walls. The combination of internal pressurization and spring tension forces pushed the walls of the cup diaphragm deeply into the grooves of the insert, which abruptly stopped the diaphragm movement and formed a good pressure seal. Live-fire ram accelerator experiments showed that projectiles with magnesium nose tips can readily penetrate the thick-walled polycarbonate diaphragms without any impact on ram accelerator performance, and that the diaphragm fragments are completely blown out of the catcher insert every time. These experimental results demonstrated that a breech-loaded diaphragm system can be readily implemented.

## **Appendix A**

# **EVALUATION OF GAS GENERATORS FOR RAPID GENERATION OF RAM ACCELERATOR GASEOUS PROPELLANTS**

by

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# 1 PROBLEM STATEMENT

Up to this time, all ram accelerator tests have been conducted in stationary test facilities and not on mobile platforms. For future battlefield applications, ram accelerator-augmented guns will have to be mounted on mobile platforms such as ships, tracked land vehicles, or heavily armed airplane gunships. Up to this time, the gas supply for stationary ram accelerator tests has always come from compressed gas cylinders. Compressed gas cylinders are very heavy and very bulky and not suitable for military applications in forward positions. Size and mass of compressed gas cylinders would make it difficult for a ram accelerator gun to quickly move into strategic positions and to remain undetected from hostile surveillance. The logistics of maintaining a reliable supply of compressed gas cylinders to a forward position would be very difficult.

The U. S. Navy envisions the use of ram accelerators as extensions of conventional guns to increase the muzzle velocity and extend the range<sup>1</sup>. There are basically two missions, one as rapid-fire interceptor projectiles to neutralize sea-skimming missiles where the detection range is limited and the response time is only of the order of seconds. The other mission is that of very long range ground support artillery where the range and stand-off distance can be extended to 100 km to keep the ship out of harm's way on heavily defended coastlines.

The original version of this study drafted in 1998 was entitled "Ram Accelerator Propellant Storage and Preparation from Battlefield-Indigenous Chemicals", but the current emphasis was shifted to identify chemical reactions in gas generators that can provide ram accelerator gases at high pressures in a very rapid and reproducible manner. These goals cannot be achieved with chemicals that are already in the battlefield (water, air, diesel fuel) alone, at least not in a rapid-fire mode of operation. Instead, the search was extended to commercially available types of pyrotechnic gas generators that can be adapted to the task at hand.

Since one of the obvious drawbacks of a gaseous propellant weapon system is the low storage density of the propellants, the current program addresses the possibility of storing propellant in solid or liquid phase. Cryogenic propellant storage is being considered by other investigators, thus the focus here is on solid gas generator schemes that can quickly release sufficient propellant mass at high pressure to enable rapid fire rates for the ram accelerator. An evaluation of available solid gas generators that can provide sufficiently high mass flow rates will be conducted. The possibility of using liquid gas generants will also be studied, but it appears at a first glance that they will require longer response times to come up to operating pressure and longer operating times to generate sufficient gas for a complete fill.

Solid propellant gas generators are already available for hydrogen, nitrogen, or oxygen. Such solid propellant charges are typically one-shot throw-away devices. Similar gas generators are being developed for chemical lasers. The advantage of solid gas generators is that they have unlimited storage life, are less prone to leakage, and require only a short burst of electrical energy for initiation. Solid hydrogen gas generators have been considered for light gas guns.

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<sup>1</sup> Kruczynski, D., F. Liberatore and M. Nusca: NAVRAM5 - An Analysis of Ram Acceleration for Specific Naval Application, ARL-TR-1073 (April 1996) Limited Distribution.

## 2 BACKGROUND INFORMATION

### 2.1 *Current Ram Accelerator Filling Techniques*

The currently used filling technique is dependent on compressed gas cylinders. The compressed gas cylinders are very bulky, only a portion of the gas can be used while the cylinders are at full pressure, and the cylinders add a significant amount of dead weight that has to be moved back and forth between the supply depot and the point of use. Using two mass flow controllers, it currently takes about 45 minutes to fill a 4-m section of a 38-mm diameter ram accelerator to an operating pressure of 20 MPa (2940 psia). The filling rate is currently limited by the flow rate of economically available mass flow controllers (20 L/min. at STP). More than two mass flow controllers could be connected in parallel if faster turnaround times between shots were required. A search could be conducted for commercially available industrial mass flow controllers with higher flow rates, but that has not been a requirement up to this time. The mixture ratio is controlled by a feedback controller employing RTD mass flow meters and switched servo-actuated valves<sup>2</sup>. For future gas generator-based gas sources, it is envisioned that the mixture ratio is controlled by the masses of three solid gas generants in the individual cartridges, one for the oxidizer, one for the fuel, and one for the diluent. The amount of gas produced by combustion of a solid gas generant is very predictable and the mixture ratio will be very reproducible. The oxidizer or fuel cartridges may even share the same housing with the diluent cartridge. For a pyrotechnic gas generator, we no longer need electronic mass flow controllers and associated mixture ratio control electronics. The absence of moving parts (valve controllers) would increase the reliability of the overall system.

### 2.2 *Physical Properties of Propellant Gases*

The physical properties of candidate propellant gases are summarized in Table 1. The boiling point and critical point indicates the temperature range in which the chemicals can be stored as liquids at room temperature. Table 1 identifies the permanent gases that can only be stored as cryogenic liquids if liquid storage is preferred over compressed gas storage. This is a summary of the ingredients as they are placed (or considered to be placed) into the ram accelerator tube, not the chemicals to be used in gas generators. In a few cases, such as evaporation from cryogenic storage, the chemical compositions of the working fluids in the as-stored and as-loaded condition are the same. Our current study does not include cryogenic storage and evaporation of propellants.

In addition to methane or ethane, there are many other hydrocarbons and hydronitrogens that could potentially be used as fuels in ram accelerators, but their vapor pressure at room temperature is too low and they might condense at the high initial loading pressures required for high-performance ram accelerators. Condensation limits the partial pressure to which the fuel ingredient can be built up in the combustible mixture. It has also been considered to inject less volatile fuels in the form of an aerosol (similar to a diesel injector), but it would be difficult to stabilize the aerosol and prevent it from settling while the shot is prepared or while the aiming mechanism locks onto the target.

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<sup>2</sup> Jardin, M. R., and A. P. Bruckner: Feedback-Controlled Gas Mixing System for the Ram Accelerator, AIAA Paper 94-0016, J. Prop. and Power **11**, 1291-1298 (1995)

### **3 TECHNICAL APPROACH**

Initially, it was proposed to generate at least some of the gases needed in the field from fuels that are commonly found in a battlefield situation, such as diesel fuel or aviation kerosene. The current study started out several years ago as a proposal to look at existing technology for generating hydrogen and/or methane from liquid hydrocarbon fuels in the field. The initial proposal, never formally submitted, was to identify candidate chemical reactions and to determine what needs to be done to adapt this technology to a mobile high-pressure ram accelerator propellant production plant. Initially the emphasis was mostly on the fuel supply, but as the concept progressed, the oxidizer and diluent gas requirements were also taken into consideration. The statement of work our current job assignment specified the task as "Examine feasibility of various propellant storage and handling techniques to provide a data base from which shipboard logistics decisions can be made in deciding between conventional compressed gas storage and alternate higher-density storage means."

While some ram accelerator applications envision two-stage or even multi-stage accelerators with different propellants used in each section, the current program is limited to single-stage ram accelerators. Again, future studies may want to look at multi-stage accelerators and the possibility of creating a wider range of propellant mixtures from gas generators.



Table 1 Physical Properties of Ram Accelerator Oxidizers, Fuels and Diluents

Ingredient	Formula	Boiling Point, K	Critical Temp, K	Critical Pres, MPa
<b>Oxidizers</b>				
Oxygen	O <sub>2</sub>	90.17	154.3	5.02
Nitrous oxide	N <sub>2</sub> O	184.65	309.65	7.242
<b>Fuels</b>				
Hydrogen	H <sub>2</sub>	20.3	33.2	1.293
Methane	CH <sub>4</sub>	111.6	191	4.626
Ethane	C <sub>2</sub> H <sub>6</sub>	361.3	305.2	4.923
Ethylene	C <sub>2</sub> H <sub>4</sub>	170.7	282.7	5.121
Ethylene oxide	C <sub>2</sub> H <sub>4</sub> O	283.8	468.9	7.171
Acetylene	C <sub>2</sub> H <sub>2</sub>	189.1	309.1	6.262
Carbon monoxide	CO	81.6	133.1	3.485
Ammonia	NH <sub>3</sub>	239.7	405.5	11.26
Hydrazine	N <sub>2</sub> H <sub>4</sub>	387.4	653	1.46
<b>Diluents</b>				
Nitrogen	N <sub>2</sub>	77.25	125.9	3.38
Carbon dioxide	CO <sub>2</sub>	194.6	304	7.363
Helium	He	0.96	5.2	0.228

A complete study for all branches of the armed forces would have to consider the fighting conditions of army ground troops, airborne weapons and naval vessels operating on a body of water. Whereas one may assume that water as a reactant or coolant may always be available for navy applications, this assumption may not be true for army applications and would certainly be erroneous for airborne weapons. The current study concentrates on specific ram accelerator propellant logistic needs for the U. S. Navy. It is hoped that the program can be expanded in the future to include ram accelerator propellant needs of the other branches of the armed services as well.

### 3.1 Summary of Gases Needed

The specification listed in Table 2 was provided by the UW principal investigator as a baseline requirement: Identify a gas generator that can supply the following masses of fuel and air components at 400 atm (calculated assuming stoichiometric mixtures and ideal gas behavior). Minimum useful fill pressure is around 200 atm, thus these masses would be halved in this case.

Table 2 Gas Requirements for Ram Accelerator Application

	CH <sub>4</sub>	C <sub>2</sub> H <sub>4</sub>	C <sub>2</sub> H <sub>6</sub>
Fuel, kg	3.9	4.7	4.3
O <sub>2</sub> , kg	16	16	16
N <sub>2</sub> , kg	51	53	53

Tube is 20 cm ID, 5-m-long, vol = 0.157 m<sup>3</sup>, 400 atm, 300 K, Ideal gas (kg)

The specified mass ratio of oxygen to nitrogen is 16 : 51 = 1 : 3.18. This is somewhat similar to the oxygen to nitrogen mass ratio in atmospheric air, which is 1 : 3.26 (not counting the argon together with the nitrogen as diluent). Thus, if one would want to draw the oxidizer and diluent from air by using a compressor, only the fuel constituent would have to be carried as a logistic supply item. However, even if the energy requirements and the space required for an air compressor and the storage tanks could be accommodated on board a ship, the time required to bring the compressed storage tanks back to full operating pressure after each shot may be prohibitive. This is one reason why we are here looking at an all-pyrotechnic gas generant scheme based on solid gas generant cartridges that can be re-loaded rapidly for rapid fire exercises and do not involve any moving parts.

In many cases the chemical processes proposed here may not be able to produce pure hydrogen, methane, ethylene or ethane. Many organic chemistry processes, such as those used in petroleum refineries, result in mixtures of reaction products instead of a pure product stream. For the ram accelerator, a pure fuel gas stream is not needed as long as the propellant mixtures are consistently and reproducibly the same and the accelerator gun performance has been tested for this particular mixture of hydrocarbons. So far, only few tests have used hydrocarbon mixtures instead of pure methane or pure ethane.

### 3.2 Ability to Deliver Gases at High Pressures

Only few of the concepts discussed herein are capable of delivering gases at the high pressures typically required for future ram accelerators (200 to 400 atm = 2936 to 5872 psia). Compressed gas cylinders can do that for only a short time, because with each shot the remaining supply pressure decreases. Much of the residual gas is useless and has to be transported back to the supply depot or has to be transferred to another cylinder with a compressor that boosts the gas pressure to a higher pressure. Boosting the supply pressure of one tank by pumping gas from two or more partially filled tanks is a slow process and requires additional energy to drive the compressor.

Concepts which are capable of rapidly supplying gases at high pressures, like pyrotechnic solid gas generators will therefore receive bonus points when it comes to evaluating the various concepts for practicality, reliability, repeatability, and operational logistics benefit. Concepts

which depend on a compressor will receive penalty points for the failure probability of moving parts and the maintenance requirements such as lubrication and periodic replacement of sliding or rotary seals in compressors.

### **3.3 Effect of Mixing Techniques on Choice of Propellant Supply**

In order to achieve optimum mixing, it would be desirable to meter all three constituents from high pressure gas sources simultaneously and pass them through a short, turbulent mixing section to achieve complete mixing in the chamber. Similar static mixing devices consisting of alternating flow splitters/diverters/turbulators are used in other fluid mixing applications. In the absence of mixing devices, there has been concern about incomplete mixing or even stratification of gas mixtures in vertical or inclined tubes. In the past, operators of some stationary ram accelerator test installations have occasionally recirculated the gas for several minutes prior to a test in an effort to achieve complete mixing before the shot was fired; however, the repeatability of the experiments was found to be very good even with moderate mixing and thus the recirculation process was discontinued.<sup>3</sup>

#### **3.3.1 Sequence of Propellant Constituent Addition**

The propellant ingredients can be added sequentially or simultaneously. Sequential addition of gases will result in gas pockets that do not mix on their own and may persist for several hours. Sequential addition has the disadvantage that a dedicated forced mixing device (gas recirculation, internal mixing fan) has to be employed to assure that the charge is uniformly mixed before the shot is fired (unless one strives for a controlled gradient to optimize acceleration of the projectile). Recirculating the gases for mixing not only requires special equipment, but it also requires time and would slow down the repetitive firing rate of the gun. Sequential mixing could be more acceptable if there is more than one gas admission port. If a large number of gas admission ports can be installed along the accelerator section of the gun, it would be possible to fill the tube with sequential gas admission and still achieve acceptable mixing quality in a short time. External gas distribution tubes attached to the center and top section of the ram accelerator extension of a hypervelocity gun would add to the weight and vulnerability of the barrel extension. It would be preferred to fill the ram accelerator only from a single lower entrance.

Multiple fill ports, equally spaced along the length of the barrel, may be required not only to achieve better mixing, but also to allow faster filling of the chamber (even if the mixing occurs at a different, upstream location of the gas supply system). UW has conducted filling tests where 8-m sections of tube were filled through four fill ports or through a single fill port<sup>4</sup>. The gas composition in the two series of experiments was essentially identical for nitrogen as the diluent, but deviations were noticed when helium was used as the diluent. Most of the mixing was occurring in the plumbing leading to the tube sections. There was no difference between samples taken immediately and after a 2.25-h hold period.

Currently the loading of ram accelerators in laboratory experiments is so slow that adiabatic heating is not a concern. The heat of compression is readily dispersed to the walls of

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<sup>3</sup> Personal communication, David Kruczynski, Utron Inc. (1993)

<sup>4</sup> Emmanuel Domingo: Evaluation of Ram Accelerator Propellant Mixing, 1997 AIAA Region VI Student Conference Paper, 18 pp. (April 1997)

the system. Otherwise, if gases are admitted to the tube at a very fast rate and rapidly compressed, adiabatic heating may be sufficient to cause premature ignition. With future rapid-fire rapid reload systems, adiabatic compression and adiabatic heating may be a limiting factor. Therefore, if the gases are already hot as they emerge from a pyrotechnic gas generator, additional adiabatic heating may cause premature ignition. Only slight cooling takes place as the gases expand isentropically from the gas generator operating pressure to the ram accelerator loading pressure. Additional active cooling of the pyrotechnically generated gases may be required to stay below the autoignition temperature of the mixtures, in particular under rapid, turbulent flow conditions and at stagnation/impingement points. If the gas charged into the ram accelerator chamber is too hot, it occupies more volume and less propellant mass can be loaded into the tube, resulting in sub-nominal performance. Although the hot gas has a higher enthalpy, the ram accelerator performance is better for a denser medium. For a filling time of 100 seconds, adiabatic loading may cause temperature increases by more than 100 K in the ram accelerator tube.

An additional consideration in selecting the burn rate and sequencing of gas generator operation is the possibility to integrate the operation of the gas generator with the mechanism required to deploy and seat the exit and entrance diaphragm at the beginning and at the end of the gas filling operation. Thus the inflation sequence of a gas generator could be tailored such that initially a slow rate of gas generation provides the pressure to gently move the exit diaphragm into position and seat it firmly. Only after the exit diaphragm has properly sealed, would the gas generator cartridge proceed to the second, fast mode of operation when the tube is filled with combustible gas mixtures at high pressures. The placement of the entrance diaphragm is less well defined. It could be emplaced before the main charge of the gas generator is ignited or it could be pushed in place by the last increment of gas exiting the gas generator, depending on if the gases enter the ram accelerator section radially at the side of the barrel or axially at the bottom of the tube.

#### **3.3.1.1 Sequential Addition of Ingredients**

Propellant gas supply concepts (compressed gas, cryogenic liquid evaporation, pyrotechnic gas generators) have different pressure ranges in which they can be optimally used. It may be quite possible that the optimum integrated system is a combination of more than one propellant supply concept. For instance, fuel gas could be generated from liquid hydrocarbons, diluent generated by evaporation of a cryogenic liquid and the mixture ultimately brought to pressure by adding the oxidizer from a pyrotechnic oxygen gas generator. Depending on the gas mixing technique chosen, the oxidizer can be the very last ingredient added to the three-component mix that ultimately has to be at the highest possible pressure. The sequence of addition could be such that the process that cannot operate at high pressure would be allowed to provide the first component, and the process that can easily provide gases at high pressure would be the last fill process to step into action, except that diluent cannot be added last for fear that the undiluted oxygen/fuel mix might detonate from an external source of ignition. (If pyrotechnic gas generators are used, the possibility of sparks penetrating the coolant section and dust filter has to be taken into consideration). Another source of potential premature ignition in the filling and mixing system is in areas of high turbulence<sup>5</sup> and potential shock formation, similar to the ignition that occurs

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<sup>5</sup> Neer, M.: An investigation of spontaneous ignition in flowing hydrogen / air mixtures, Ph. D. Dissertation, Ohio State Univ. (1972)

on the surface of the ram accelerator projectile by machining a step into the cone or by turbulence in the wake of a perforated obturator plate.

If it can be shown that premixing of undiluted oxidizer and fuel is not prohibitive from a safety standpoint, the diluent could be added last from a pyrotechnic nitrogen gas generator. This would be a preferred mode of operation, because pyrotechnic nitrogen gas generators require less development work than high-pressure oxygen or even high-pressure fuel gas generators. Pyrotechnic nitrogen generators can safely operate at pressures of several thousand psi. Pyrotechnic nitrogen gas generators have a substantial industrial experience base in the current, well-established applications as airbag inflators and fire extinguishing systems. The design of a nitrogen gas generator for a ram accelerator could be derived from existing airbag inflator designs.

Axial mixing of gas clouds in long, horizontal cylinders has been studied in an effort to deliberately establish desirable concentration gradients in long ram accelerator tubes to adjust the speed of combustion to the speed of travel of the projectile as the projectile travels and accelerates through the ram accelerator section<sup>6</sup>. It was suggested that axial gradients along the ram accelerator tube may persist for hours. If sequential firing of gas generators is seriously considered for the current program, additional mixing studies will need to be conducted to assure uniform and reproducible mixing of the gas components. A limited amount of modeling using Fick's laws of gas diffusion may be useful to support the experiments. Another concern is the stratification of mixtures that were initially perfectly mixed. Stratification may take place if the barrel is not horizontal (as in current lab experiments), but elevated in an actual long-range firing position and the gun is kept in the ready-to-fire state for a long time. Stratification problems would be most pronounced if hydrogen is used as the fuel or helium is used as the diluent.

The sequence of gas addition must also consider the fact that under actual use conditions, the tube may be filled with exhaust gas from a previous shot or it may contain air that diffuses into the tube before the new set of diaphragms can be put into place.

### ***3.3.1.2 Simultaneous Addition / Instant Mixing of Ingredients***

The preferred method of filling the ram accelerator chamber would be the admission of a thoroughly mixed gas from only one fill port. This is the technique currently used in stationary installations with gases drawn from compressed gas cylinders and metered with proportional mass flow controllers. There is sufficient turbulence in the plumbing system between the point of confluence and the entry into the ram accelerator chamber that mixing is complete by the time the gases enter the chamber<sup>7</sup>. Once the compressed gas cylinders are replaced by pyrotechnic gas generators, the ignition sequence of the three (or two) pyrotechnic devices has to be timed such that the gas flow at the point of convergence is in the proper ratio and the mixing ratio is constant. It is possible to combine the nitrogen gas generator and the oxygen gas generator in one common pressure shell, since they can operate at the same pressure. Rocket Research Company (RRC) once developed and tested an "air generator" for inflation of airbags which produced nitrogen and oxygen gas in a 4:1 volume ratio similar to that of atmospheric air. This was done in response to toxicologists' concerns that filling an automobile with nitrogen from

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<sup>6</sup> Kepler, C. E., et al.: Ram-Cannon Propulsion Concept, Volume II: Technical Evaluation, United Technologies Research Center, Report R86-957219-8, ARFSD-CR-86024, 269 pp., Contract DAAA21-85-C-0153 (Apr 1986; publ. Jan 1987); DoD Limited Distribution.

<sup>7</sup> Emmanuel Domingo: Evaluation of Ram Accelerator Propellant Mixing, 1997 AIAA Region VI Student Conference Paper, 18 pp. (April 1997)

inflation of multiple airbags might asphyxiate the occupants due to lack of oxygen. (Most accidents with airbag inflations leave the car in a venting condition and this concern was later put to rest).

In 1971, RRC conducted two tests with an air generator (instead of a nitrogen gas generator) where groups of rats were exposed to nearly undiluted exhaust for 30 minutes without any undue effects (this would be equivalent to sticking one's head into the inflated bag after an airbag deploys). The gas generants used in these tests were RRC-112 (oxygen candle formula) and RRC-310A (a hot-burning potassium perchlorate/sodium azide propellant). Other companies<sup>8</sup> involved in airbag developments have also described air gas generators, but applications are not known.

A similar pyrotechnic air generator could be developed to generate mixtures of nitrogen and oxygen in the ratio prescribed by the ram accelerator requirements. The gas generant pellets might still be burning in separate sections of the gas generator to minimize the formation of  $\text{NO}_x$  during the combustion reaction. In a cylindrical gas generant cartridge, the two gas generants could be arranged concentrically (Figure 1). They might share the common coolant and dust filter section and certainly would share the pressure hull. The dust filter for slow (15 minute burn time) operation is much smaller than a dust filter required for a 15-second fill time of a ram accelerator. There is a trade-off between operating time and filter size.

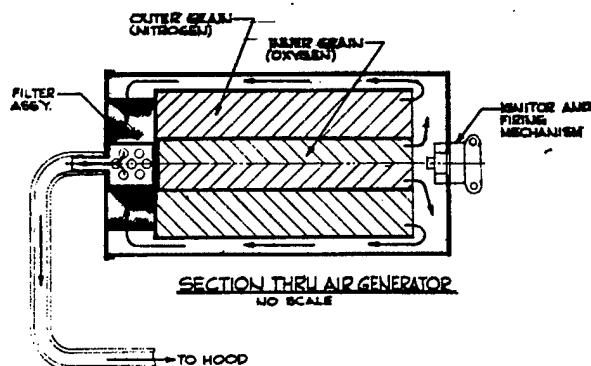


Figure 1 Pyrotechnic air generator (from Pietz and Steinle 1978)

Even if the three gases are generated simultaneously, the design of the mixing station plumbing must arrange the feed ports such that no premature ignition can take place where the three gases mix. For that reason, fuel and diluent should be mixed first and the oxidant could be added last. Another option would be to mix oxidant and diluent first and add the fuel last. However, the prime objective of the current study was to identify the gas generants, and the specific design of a mixing station must be done under a subsequent effort.

### 3.3.2 Instant Readiness Requirement

For military applications, instant readiness of the gun to perform defense or attack duties is an important consideration. With compressed gases, instant readiness is assured as long as the compressed gas cylinder has enough pressure. If the burst discs in the ram accelerator are leak-

<sup>8</sup> Pietz, J. F., and M. E. Steinle: Pyrotechnic Air Generator, SAFE Journal Vol. 8, No. 3, p. 13-15 (1978)

proof, the ram accelerator tube itself could be maintained in a loaded condition during a period of alert. With pyrotechnic solid gas generants, instant readiness is assured similar to the spontaneous reaction of conventional solid gun propellants. It should be noted that the exhaust of most conventional gun propellants is fuel-rich as evidenced by the muzzle flash as soon as the hot gases exit into surrounding air. Additional study will need to look into the feasibility to tailor existing double-base gun propellants to generate fuel-rich gases consisting mostly of methane, ethane, and carbon monoxide.

Solid gas generants can supply gases at a moments notice, as vividly demonstrated with automobile airbag gas generators which have to operate within milliseconds of an automobile collision. A slight disadvantage of solid gas generants is that they don't have the good hydrogen storage density of some of the liquid fuels and that we do not (yet) have a solid gas generant that supplies pure methane or ethane.

It would be logistically superior if the fuel gas could be generated from liquid fuels already onboard the navy ships. A disadvantage of the proposed chemical gas generation schemes starting with diesel fuel or other fuels already onboard of navy ships is the long warm-up time before the catalytic gas generators come to full operation. The startup time could be shortened by keeping the catalytic reactors hot all the time during stand-by and alert, but that has an energy penalty.

### **3.4 Solid Gas Generants**

Solid gas generants are available for a wide range of gases. Most solid gas generants are pyrotechnic mixtures which are ignited by a squib (electric bridge wire initiator). The mode of operation is similar to that of gun powder in an artillery or gun cartridge. Pyrotechnic mixtures are known which produce oxygen, nitrogen, hydrogen, and deuterium. Some solid gas generants have even been developed that can produce elemental fluorine, nitrogen trifluoride and other fluorine compounds. These fluorine compounds were intended to be used in chemical lasers. For the same application, pyrotechnic gas generators capable of generating hydrogen, deuterium or nitrogen have been developed. The technology from these gas generators can now be applied to generate gases for ram accelerators. Unfortunately, technical detail from the laser gas generator developments are classified or limited and cannot be discussed at this place. It is possible to include that information in a classified addendum to the current study. A common disadvantage of solid gas generants is that they do not combust without residues (slags and ashes) and smoke particles have to be filtered from the hot gas stream for most of the uses before the gas can be used for the intended purposes. The other disadvantage is that the as-generated, pyrogenic gases are very hot and have to be cooled before they can be safely used for the intended application, for instance, inflating an airbag or supplying emergency oxygen for breathing of occupants in enclosed spaces.

Nitrogen gas generants are the predominant source of high-pressure gas for the inflation of "air" bags supplemental restraint systems in passenger automobiles.

Hydrogen gas generants have been proposed for the inflation of weather balloons, for hypervelocity guns, and as a fuel source for chemical laser weapons.

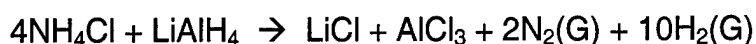
The various types of solid gas generants will be discussed in the following sections in more detail. The following section is arranged by the type of gas produced. The chapters are in the sequence fuel, oxidizer, diluent. This sequence parallels the amount of each ram accelerator

propellant required, starting with a small mass of fuel, a larger mass of oxidizer, and a significant mass of diluent. A later chapter is devoted to liquid gas generants.

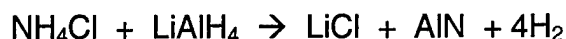
### 3.4.1 Solid Gas Generants for Production of Hydrogen

Hydrogen gas generators have been developed for the inflation of weather balloons, rescue markers, fuel cells, light gas guns and chemical lasers. As far as the light gas gun or laser applications are concerned, technical details from these gas generator developments are classified or limited and cannot be discussed at this place. A classified or limited addendum to this report can be prepared if warranted.

U. S. patent 3,898,048 describes mixtures of ammonium chloride and lithium aluminum hydride and methods for their ignition<sup>9</sup>:

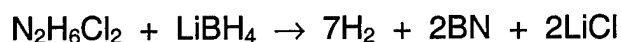


For our application the dilution of hydrogen with nitrogen is no disadvantage, as long as the H : N mixture ratio remains always the same and is predictable. This reaction is not exothermic and it is unlikely that the reaction will proceed in this direction. Some of the nitrogen may also end up as aluminum nitride which would give hydrogen of a higher purity:



The real condition is somewhere between the two reactions. For chemical laser applications using deuterium instead of hydrogen, a mixture of  $\text{LiAlD}_4$  and  $\text{ND}_4\text{Cl}$  was selected for use in a pelletized bed, and was test fired at the 1500-g level at a burning rate of  $0.064 \text{ cm/s}$ <sup>10</sup>.

Using hydrazinium salts instead of ammonium salts results in a more exothermic reaction<sup>11, 12</sup>,



The U. S. Army Missile Command in Huntsville<sup>13, 14</sup> tested various gas generators for hydrogen or deuterium generation for  $\text{F}_2/\text{H}_2$  or  $\text{F}_2/\text{D}_2$  chemical lasers. The formulations tested at MICOM are summarized in Table 3.

Pressed pellets of the first formulation in Table 3 were used for burning rate studies. It was unusual that the material has a negative burn rate coefficient. The burn rate was  $483 \text{ mm/s}$

<sup>9</sup> Barber, W. H., W. F. Beckert, and O. H. Dengel: Light-weight rocket deployable gas generator, U. S. Pat. 3898048 (21 Mar 1974/5 Aug 1975)

<sup>10</sup> Bowen, R. E., et al.: Solid Gas Generators for Chemical Lasers, Naval Surface Weapons Ctr., White Oak Lab., Silver Spring, MD, Tech. Rept., 14 pp. (Jan, 1976); AD-A042674; PIRSU 1978-0005

<sup>11</sup> Beckert, W. F., O. H. Dengel and R. W. McKain, Hydrogen Generating Compositions, Dept. Navy, U.S. Pat. Appl. 152422, U. S. Pat 3734863 ( / May 1973), 3 pp., AD-164962

<sup>12</sup> Beckert, W. F., O. H. Dengel, and R. W. McKain, Hydrogen Generating Compositions and Methods, U.S. Navy, U.S. Pat. 3862052 (23 Feb 1973/21 Jan 1975)

<sup>13</sup> Ayers, O. E., et al.: Solid Propellants for Hydrogen Gas Generators, MICOM, Preprint, 12 pp. (1976), AD-A025974; CA 85, 162873

<sup>14</sup> Ayers, O. E., et al.: Solid Propellants for Generating Hydrogen, MICOM TR RK-76-11, Technical Report, 17 pp. (Apr 1976), AD-A029353



at 3.45 MPa (500 psia) and 4.06 mm/s at 13.8 MPa (2000 psia). Other investigators had also observed negative coefficients in their formulations of hydrogen generating propellants. Some pyrotechnic materials are hard to ignite if the chamber is pre-pressurized with hydrogen gas because of the high thermal conductivity and high heat capacity of this gas. The third formulation generated a gas mixture containing 90 vol% H<sub>2</sub>, 4 % N<sub>2</sub> and 5 % NH<sub>3</sub>. The ammonia interferes with the laser application, but it would not be a detriment to ram accelerator operation.

Looking at the reactants in these hydrogen-forming reactions, it is sometimes difficult to say which is the oxidizer and which is the fuel. Some of these reactions are merely metathetical reactions where hydride hydrogen is oxidized to molecular hydrogen. We assume that the hydride is the fuel. Sodium hydride has even been tested as a source of hydrogen for a fuel-cell powered car in Germany. It is becoming more readily available if more applications for this chemical can be found.

Table 3 Hydrogen Gas Generant Formulations Tested at MICOM

Chemical Reaction	Wt% Oxidizer	Wt% Hydride	Density, g/cm <sup>3</sup>	H <sub>2</sub> Generation, mL (STP)/g
$3\text{NaBH}_4 + 2\text{Fe}_2\text{O}_3 \rightarrow 3\text{NaBO}_2 + 4\text{Fe} + 6\text{H}_2$	74	26	2.61	311
$3\text{LiBH}_4 + 2\text{Fe}_2\text{O}_3 \rightarrow 3\text{LiBO}_2 + 4\text{Fe} + 6\text{H}_2$	83	17	2.41	349
$2\text{NaBH}_4 + (\text{NH}_4)_2\text{SO}_4 \rightarrow 2\text{NaBO}_2 + \text{N}_2 + 7\text{H}_2 + \text{H}_2\text{S}$	46.6	53.4	1.32	755
$2\text{LiAlH}_4 + 2\text{NH}_4\text{Cl} + \text{Fe}_2\text{O}_3 \rightarrow \text{Al}_2\text{O}_3 + 2\text{LiCl} + 2\text{Fe} + \text{N}_2 + 8\text{H}_2$	31.2 NH <sub>4</sub> Cl, 46.6 Fe <sub>2</sub> O <sub>3</sub>	22.16	1.87	523

The controlled thermal decomposition of hydrazine bisborane<sup>15, 16</sup> is an attractive solid source of hydrogen, yielding 1.88 L H<sub>2</sub>/g. Combustion of hydrazine bisborane, a solid hydrogen gas generant, produces hydrogen and boron nitride (a solid):



Usually solid residue formation is a disadvantage in gun applications. Boron nitride formation may be an exception because boron nitride is an excellent solid lubricant.

It should be possible to change the formulations of the hydrogen producing pyrotechnic mixtures above such that they produce not only pure hydrogen, but mixtures of hydrogen and methane. This can be achieved by including small percentages of organic compounds or metalorganic compounds. An undesirable side reaction in these reducing atmosphere gas mixtures with organic compounds in the presence of nitrogen would be the formation of hydrogen cyanide, a thermally stable, frequently observed by-product of fuel-rich combustion in

<sup>15</sup> Barber, W. H., W. F. Beckert, and O. H. Dengel, Solid State Hydrogen Gas Generator, AIAA Paper 73-1232 (1973)

<sup>16</sup> Fifer, R. A., and I. C. Stobie, Combustion Thermodynamics of Some Boron Nitrogen Hydrogen Compounds, CPIA Publ. 383 Vol. 1, 20<sup>th</sup> JANNAF Comb. Mtg., 611-619 (Oct 1983) AD-A138033; PIRSU 1984-0036DDD

the presence of nitrogen compounds, and a typical constituent of double-base gun propellant exhaust.

### 3.4.2 Solid Gas Generants for Hydrocarbon Mixtures

As indicated before, we have not been able to identify a solid gas generant that produces exclusively methane, ethane or ethylene. However, it is possible to obtain a mixture of hydrocarbons from the pyrolysis of organic binders such as polyethylene, polypropylene or polybutadiene in a pyrotechnic reaction. Most gun propellants produce fuel-rich mixtures of gases as evidenced by the (often unwanted) muzzle flash as soon as the hot gases come into contact with air. We have started to assemble a list of well-characterized gun propellants and we are searching for extremely fuel-rich formulations that could be used to generate high-pressure fuel gases for a ram accelerator. The actual composition of many gun propellants is either proprietary or security-restricted or both. We need to regain authorization to use the CPIA Solid Propellant Manual<sup>17</sup> and the CPIA Solid Propellant Ingredients Manual<sup>18</sup> to make a more educated selection of an optimum gun propellant for this application. The resultant report will then also have security restrictions. We have selected here a few unclassified gun or rocket propellants for which we happened to have the input information and we have calculated the theoretical performance as a rocket propellant and the exhaust gas composition using the PEP2100 program. We shall have to expand this list to include solid propellants that were previously excluded from other applications (airbag inflation, emergency escape slide inflation) due to the high flammability of their exhaust gases in air. The high flammability becomes now a desirable attribute. Whereas gun propellants have been selected for their high impetus and low muzzle flash, we are now adding another evaluation criterion: fuel-rich exhaust gas compositions. Many of the more recently developed gun propellants contain RDX (nitramine propellants) in an effort to improve thermal stability and low-vulnerability (LOVA) properties. However, RDX nitramine propellants burn hotter and have a less combustible exhaust than conventional double-base propellants. It is more likely that our propellant of choice will be a slow-burning, cool-burning double-base propellant with a high plasticizer content, similar to AGJ.

Table 4 lists the theoretical exhaust composition of some typical gun propellants (sorted by increasing flame temperature). We are listing the chamber compositions at 6.8 MPa (1000 psia) for comparison. The chemical composition changes during expansion and cooling of the gases. The calculations will be repeated for gas generator operating pressures of 3.4 to 6.8 MPa (500 to 1000 psid) above the desired delivery pressure of the gases, and the effect of isentropically expanding from the gas generator operating pressure to the delivery pressure will be calculated. The addition of nonreactive coolants (heat sinks) or reactive coolants can also be programmed into the ingredients input list. The numbers in Table 4 do not add up to 100 because minor trace species present in concentrations below 1000 ppm were omitted. The best candidate gun propellant on this preliminary list is AGJ. It has a low flame temperature and a high combustibles content. We have not included any composite propellants containing ammonium nitrate or ammonium perchlorate because they lack thermal stability or result in formation of corrosive exhaust (HCl). We have also eliminated composite-modified double-base

<sup>17</sup> Chemical Propulsion Information Agency, Solid Propellant Manual, CPIA/M2, Loose-leaf ring binder, periodically updated, CONFIDENTIAL, NOFORN

<sup>18</sup> CPIA Solid Propellant Ingredients Manual, CPIA/M3, Loose-leaf ring binder, periodically updated, NOFORN

propellants from further consideration because they are burning hotter than double-base propellants and thus more coolant material would be required to bring down the temperature to the desired 298 K delivery temperature.

Table 4 Theoretical Composition of Gun Propellant Combustion Chamber Gases at 6.8 MPa

Propellant	Chamber Temp., K	Composition, Vol%					
		CO	CO <sub>2</sub>	CH <sub>4</sub>	N <sub>2</sub>	H <sub>2</sub>	H <sub>2</sub> O
AGJ	1387	46.5	4.8	1.8	8.0	30.4	6.5
N-5	2291	45.8	8.4	<0.01	10.8	17.3	17.5
WC-891	2601	47.9	6.9	<0.01	9.9	18.2	16.7
JA-2	2799	36.9	13.6	<0.01	12.6	10.3	26.1

### 3.4.3 Solid Gas Generants for Production of Oxygen

Oxygen gas generants, also called "oxygen candles" are used in emergency oxygen supplies, for instance in the Lockheed L-1011 Tri-Star, the Mir space station, the International Space Station, and in many submarines.

The operating pressure of oxygen candles for breathing oxygen applications is very low compared to the operating pressure of airbag inflators or other pyrotechnic devices. Additional engineering work will be required to adapt oxygen candles to high-pressure operation. One concern is the increased flammability of metals of construction of the gas generators if the operating pressure is increased. The load-bearing metal shell of the gas generator will have to be protected from the hot gases by ceramic, noncombustible liners with good thermal insulation properties. A schematic of a typical oxygen gas generator is shown in Figure 2. Oxygen gas generators come in different sizes, depending on the size of the aircraft and the number of occupants (Figure 3).

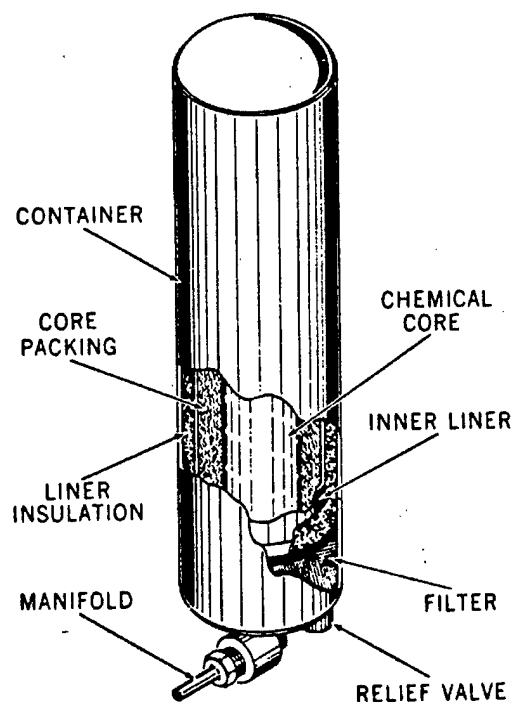


Figure 2 Schematic of a typical oxygen gas generator (from Harwood 1971)

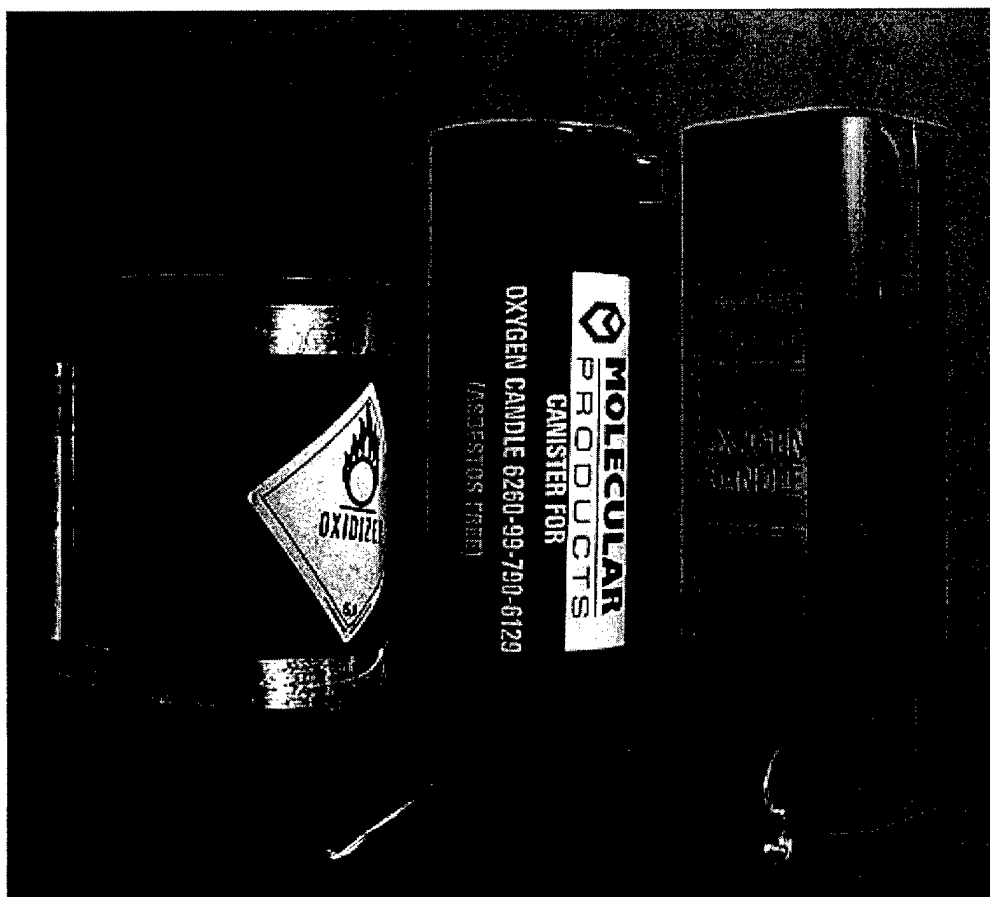


Figure 3 Oxygen Candles Manufactured by Molecular Products, Ltd.

All pyrotechnic oxygen generators use mixtures of alkali metal chlorates or perchlorates with a combustible metal powder. An inert metal oxide diluent is added to slow down the reaction and allow operating times of up to hours. The following reactions are being used or have been considered at one time in oxygen candles:



or, the same reaction with an extra molecule of lithium perchlorate:



Another patented<sup>19</sup> oxygen candle composition consists of 85-93% lithium perchlorate, 0-8% barium peroxide, 1-22% iron powder, 1.5-3% boron, and 3-4% copper fibers. See also

<sup>19</sup> Gustafson, P. R., and R. R. Miller: Lithium Perchlorate Oxygen Candle, U.S. Pat. 3,174,936 ( /23 Mar 1965)

additional patents<sup>20</sup>. Some formulations contain sodium dichromate both as a source of oxygen and as a catalyst.

The oxygen candles on the Russian Mir space station contained lithium perchlorate<sup>21</sup> and magnesium and an alkaline earth metal oxide (MgO or CaO) or transition metal oxide (manganese(IV) oxide). A similar system is now in use on the International Space Station<sup>22</sup>.

A wide range of metal oxides has been evaluated as catalysts for the thermal decomposition of chlorates<sup>23</sup>. It has been noticed that calcium oxide is as good a catalyst as some of the transition metal oxides and it is less toxic<sup>24, 25, 26</sup>. It can also be added in the form of calcium peroxide CaO<sub>2</sub>. One of the main considerations in the selection of oxygen candle formulations is the low combustion temperature and minimization of cooling requirements to cool the gas to body temperature and safe breathing temperatures. For the ram accelerator application it would also be desirable to cool the gas to room temperature before injecting it into the ram accelerator to allow rapid loading. Another reason the oxygen has to be cooled from the temperature at which it originates is to avoid ignition at the point where it is mixed with the (diluted) fuel.

Contaminants of oxygen gas generated by oxygen candle operation are salt dust and traces of free chlorine. The tolerable specification limit of free chlorine in the breathable gas is 0.3 ppm<sup>27</sup>. Various designs of filters<sup>28</sup> are patented to effectively remove dust and chlorine to make the gas breathable. Some oxygen candles pass the gas through a cartridge of hopcalite catalyst to remove traces of carbon monoxide. This is not necessary for the ram accelerator application. In addition to using fibrous material or porous materials as dust filters, coarser dust particles could be eliminated in a ram accelerator gas generator application by cyclone filters, taking advantage of centrifugal forces to separate gas and particles ("critter catcher"). Cyclone filters can be designed for continuous operation with little maintenance. These filters would be useful for any type of gas generators, regardless if the product gas is oxygen, nitrogen, hydrogen or methane.

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<sup>20</sup> Zhang, Y., et al. (Puritan Bennett Corp.): Chemical Oxygen Generator, U.S. Pat. 5198147 (10 Apr 1991/30 Mar 1993)

<sup>21</sup> Klyucharev, V., et al.: The cooperative processes of magnesium oxidation in perchlorate mixtures with oxide, 26th Intl. Annual Conf. ICT, Karlsruhe, Germany (Jul 1995), p. 64-1 to 64-11; A96-13091

<sup>22</sup> Graf, J., et al.: Development of a solid chlorate backup oxygen delivery system for the International Space Station, SAE Paper 2000-01-2348 (Jul 2000); A01-28718

<sup>23</sup> Iwakura, H., et al.: Oxygen evolution from KClO<sub>3</sub> catalyzed by metal oxides as air bag inflators, I&EC Res. **30**, 778-783 (1991)

<sup>24</sup> Klyucharev, V., et al.: The Cooperative Processes of Magnesium Oxidation in Perchlorate Mixtures with Calcium Oxide, in: Pyrotechnics: Basic Principles, Technology, Application, 26<sup>th</sup> Intl. Annual Conf. ICT (Jul 1995), Paper 64-1 through 64-11; PIRSU 1997-1461

<sup>25</sup> Klyucharev, V., et al.: Calcium Compounds as the Components Increasing the Ecological Safety of Pyrotechnic Oxygen Sources, in: Pyrotechnics: Basic Principles, Technology, Application, 26<sup>th</sup> Intl. Annual Conf. ICT (Jul 1995), Paper 65-1 through 65-12; PIRSU 1997-1462

<sup>26</sup> Klyucharev, V., et al.: Thermal analysis of binary mixtures of CaO, CaO<sub>2</sub>, Ca(OH)<sub>2</sub> and Mg(OH)<sub>2</sub> with sodium and potassium perchlorates (in Russian), Izv. Akad. Nauk, Ser. Khim. **1996**, No.1, 33-38 (1996); CA **125**, 200051

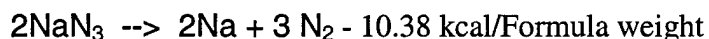
<sup>27</sup> Society of Automotive Engineers, Inc.: Determination of Chlorine in Oxygen From Solid Chemical Oxygen Generators. (SAE Standard) SAE ARP-1320A, 6 pp. (Jan 1991)

<sup>28</sup> Smith, S. H., J. K. Musick and R. R. Miller: Filtration of Salt Smoke from Chlorate Candle Oxygen, Naval Research Lab Washington D C., Report NRL-6216, 2 pp. (Feb 1965); AD-612185

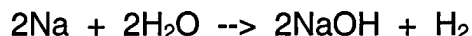
The oxygen gas generators have long shelf lives similar to airbag inflators and ejection seat cartridges. Test methods have been established to assure the service life of these units<sup>29</sup>. Although all breathing gas oxygen generators have slow burning rates and operating times of the orders of minutes, the burning rates can be adjusted by burning rate enhancers and the mass flow rate can be increased by using smaller pellets. The output rate can be tailored by selecting proper pellet shapes (e.g., perforated pellets) and pellet size.

### 3.4.4 Solid Gas Generants for Production of Nitrogen

The most convenient source for generation of pure nitrogen from solid gas generants is the decomposition and combustion of metal azides. The azide ion combines three nitrogen atoms in a very energetic molecule. The parent acid of all azide salts, hydrazoic acid (also called hydrogen azide,  $\text{HN}_3$ ) is extremely detonable both in the liquid and gaseous state and cannot be safely handled as such. Otherwise, it would be a good source of a hydrogen/nitrogen mixture. Many of the azide salts are friction sensitive, such as lead azide and silver azide which are even used in percussion primers in ammunition cartridges. The alkaline metal azides, mainly sodium azide,  $\text{NaN}_3$ , are relatively stable and form the basis of a wide range of solid gas generants for generation of nitrogen gas. Sodium azide does not decompose unless heated above 650 K. The onset of exothermic decomposition is at 643 K (370°C). The decomposition of sodium azide leads to nitrogen and metallic sodium. Because sodium azide has a positive enthalpy of formation (+5.19 kcal/mol), this reaction is mildly exothermic and becomes self-sustaining under favorable conditions:



In spite of this explosive hazard potential, sodium azide is only classified as a Poison-B for transportation and not as an explosive. A nitrogen gas generator based solely on the exothermic decomposition of sodium azide would be too slow for most practical applications. However, the metallic sodium formed in the primary reaction would be a potential source of hydrogen if the sodium is reacted with water in a secondary reaction:



Since there would be plenty of water available for most navy applications, this is a new scheme to generate both nitrogen and hydrogen from the same source. The second reaction is exothermic and the heat generated during the secondary reaction could be used to sustain the primary reaction in a counter-current heat exchanger. The gas mixture formed in this way would consist of 25 vol% hydrogen and 75 vol% nitrogen. For our application with secondary reaction with water the sodium metal vapor in the exhaust would be desirable. For airbag applications, free sodium is highly undesirable. Commercial airbag inflator mixtures based on sodium azide are formulated such as to minimize the amount of free sodium because sodium is more difficult to filter than sodium oxide and there is concern about the reactivity of the residual sodium in the inflator during disposal of spent units by immersion in water (the author has witnessed several hydrogen/air explosions during the disposal of spent airbag inflators). We are now suggesting

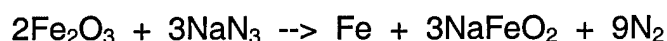
<sup>29</sup> Society of Automotive Engineers, Inc.: Useful Life Determination Chemical Oxygen Generators (Revised Mar 98). (SAE Standard) SAE ARP-1894A, 5 pp. (Mar 1998)

that we could deliberately include a small amount of chemically bound ( $\text{CaSO}_4 \times \text{H}_2\text{O}$  = hydrated plaster of Paris) or encapsulated water in the propellant mixture to generate a small percentage of hydrogen along with the bulk of the nitrogen.

In most airbag applications, sodium azide is the fuel and it is combined with an oxidizer, such as copper(II) oxide or iron(III) oxide:



Early airbag inflators used copper(II) oxide as the oxidant. Iron(III) oxide formulations burned too slowly and required the addition of 2% potassium nitrate oxidizer to increase the burning rate (RRC-852). The reaction of iron(III) oxide with sodium azide leads to a mixture of sodium oxide and sodium ferrates<sup>30</sup>. The slag formed as a reaction product or the dust carried away with the gas may also contain elemental iron and elemental sodium:



Both equations above include the formation of sodium ferrate(III),  $\text{NaFeO}_2$ . Because the thermochemical data for sodium ferrate(III) are not commonly contained in thermochemical equilibrium computer programs like PEP or HSC, a simplified equation is used here to calculate the thermochemistry of this reaction:



Many gas generant formulations contain additives of fumed silicon dioxide or clay to form a "klinker", a slag that still maintains the shape of the original gas generator pellet after the reaction is complete. This reduces the solids load that has to be filtered by the filter. Specifications will have to be derived for the ram accelerator application to specify the tolerable amount of dust in the gas. The specification will be less stringent than current specifications for airbags or emergency oxygen supplies since the ram accelerator gas does not have to be breathed. Dust content of the gas delivered to the ram accelerator should be low enough to prevent clogging of orifices, filters, or feed lines and should prevent the jamming of sliding surfaces at the breech or the diaphragm emplacement mechanism. Excessive amounts of dust may also cause erosion of the projectile or suppress the flammability of the gas/aerosol mixture. Dust would also contribute to the muzzle signature and make the position of the ship more visible.

Using potassium perchlorate instead of metal oxides as the oxidant results in a very rapidly and very hot burning formulation (RRC-311) that is used mostly in small quantities as a booster between the pyrotechnic squib and the main charge to ignite the gas generant main charge.



<sup>30</sup> Ismailov, M. B., and A. N. Leonov, Study of Stages in Reaction of Sodium with Iron Oxides in Combustion Wave (translated from the Russian), Comb., Explos., Shock Waves **26**, 264-268 (1990); CA **113**, 135221

This formulation has a higher gas output per unit mass because  $\text{KClO}_4$  is a better oxidizer and contains more oxygen than  $\text{Fe}_2\text{O}_3$ . Another unusual oxidizer for sodium azide is polytetrafluoroethylene  $(\text{CF}_2)_n$  ("Teflon").



Because  $(\text{CF}_2)_n$  is a lightweight molecule, the gas output of this mix is very good. This mixture is acceptable for industrial or military applications, but not suitable as an airbag propellant. Other non-automotive gas generant applications used sodium sulfate or calcium sulfate (plaster of Paris) as the oxidizer. Various modifications of the  $\text{NaN}_3$ - $\text{Na}_2\text{SO}_4$ - $\text{NaNO}_2$ - $\text{NaNO}_3$  system were studied with the objective of developing a propellant formulation which eliminated free sodium in the combustion residue<sup>31, 32</sup>.

The stoichiometric composition, gas formation and theoretical thermochemical heat release data for several pyrotechnic reactions considered here are summarized in Table 5. One important parameter is the amount of gas formed per mass unit of gas generant burned. This number needs to be compared to the mass required to supply an equivalent amount of gas using conventional compressed gas cylinder techniques.

The numbers shown in Table 5 are all for stoichiometric oxidizer:fuel ratios, resulting in maximum flame temperatures (not desirable) and not necessarily resulting in the optimum gas output. Actually used solid gas generants are typically fuel-rich to avoid formation of  $\text{NO}_x$  and to result in better nitrogen or hydrogen output. Actually used oxygen candle formulations are oxidizer rich to result in higher oxygen output and to reduce the flame temperature. Optimization of oxidizer:fuel ratios of the various gas generants is a separate development task. This type of experimental work is mostly done to optimize and tailor the burn rate which cannot be predicted from computer calculations.

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<sup>31</sup> Knowlton, G. D. (Talley Ind.): High Yield Nitrogen Gas Generators, 1983 JANNAF Propulsion Meeting, CPIA Pub. 370, Vol. II., p. 9-18 (Feb 1983); PIRSU 1983-0074B

<sup>32</sup> Artz, G. D., and J. E. Flanagan (Rocketdyne): High Yield Nitrogen Generators, 18th JANNAF Combustion Meeting, CPIA Pub. 347, Vol. II., p. 433-438 (Oct 1981); PIRSU 1981-0766KK



Table 5 Stoichiometry, Gas Formation and Heat Release of Gas Forming Reactions of Solid Gas Generants

Equation	Oxidizer, mass%	Gas Generant Density, g/cm <sup>3</sup>	Heat Release*, kJ/FW @ 273 K	Heat Release, kJ/g, @ 273 K	Gas Release, L/g @STP	Gas Output, mass% of gas generant
<b>Diluent Gas Generants</b>						
$6\text{NaN}_3 + \text{Fe}_2\text{O}_3 \rightarrow 3\text{Na}_2\text{O} + 2\text{Fe} + 9\text{N}_2(\text{G})$	29.048	2.28	-555.550	-1.01	0.367	45.86
$8\text{NaN}_3 + \text{KClO}_4 \rightarrow \text{KCl} + 4\text{Na}_2\text{O} + 12\text{N}_2(\text{G})$	21.036	1.96	-1846.656	-2.804	0.409	51.05
$2\text{NaN}_3 + (\text{CF}_3)_n \rightarrow 2\text{NaF} + \text{C}(\text{S}) + 3\text{N}_2(\text{G})$	27.778				0.374	46.67
$\text{NaN}_3 \rightarrow \text{Na} + 1.5\text{N}_2$	0	1.85	-21.035	-0.32	0.517	64.6
$\text{N}_2(\text{L}) \rightarrow \text{N}_2(\text{G})$	0	0.808 @ 77 K	+5.576 @ 77 K	+0.199 @ 77 K	0.800	100
<b>Fuel Gas Generants</b>						
$\text{NH}_4\text{Cl} + \text{LiAlH}_4 \rightarrow \text{LiCl} + \text{AlN} + 4\text{H}_2$	58.495	1.196	-295.065	-3.227	0.980	8.82
$\text{H}_3\text{B} \bullet \text{NH}_2\text{---NH}_2 \bullet \text{BH}_3 \rightarrow 5\text{H}_2 + 2\text{BN}$	0	0.94	-383.2	-6.418 @ 298 K	1.877	16.88
$\text{CH}_4(\text{L}) \rightarrow \text{CH}_4(\text{G})$	0	0.415 @ 109 K	+8.17 @ 111.7 K	0.511 @ 111.7 K	1.401	100
$\text{C}_2\text{H}_6(\text{L}) \rightarrow \text{C}_2\text{H}_6(\text{G})$	0	0.546 @ 185 K	+15.94 @ 185 K	0.531 @ 185 K	0.745	100
$\text{C}_2\text{H}_4(\text{L}) \rightarrow \text{C}_2\text{H}_4(\text{G})$	0	0.658 @ 171 K	+13.543 @ 171 K	0.483 @ 171 K	0.799	100
$\text{H}_2(\text{L}) \rightarrow \text{H}_2(\text{G})$	0	0.071 @ 20 K	+0.915 @ 20 K	+0.457 @ 20 K	11.21	100
<b>Oxidant Gas Generants</b>						
$3\text{NaClO}_3 + 2\text{Fe} \rightarrow 3\text{NaCl} + \text{Fe}_2\text{O}_3 + 3\text{O}_2$	74.086	3.023	-984.21	-2.283	0.156	22.27
$\text{LiClO}_4 + 2\text{Mg} \rightarrow \text{LiCl} + 2\text{MgO} + \text{O}_2(\text{g})$	68.639	2.160	-1229.938	-7.935	0.145	20.64
$2\text{H}_2\text{O}_2(\text{L}) \rightarrow 2\text{H}_2\text{O}(\text{L}) + \text{O}_2(\text{G})$	100	1.408	-196.139	-2.88	0.329	47.06
$\text{O}_2(\text{L}) \rightarrow \text{O}_2(\text{G})$	100	1.144 @ 90 K	+6.815 @ 90 K	+0.213 @ 90 K	0.700	100
$\text{N}_2\text{O}(\text{L}) \rightarrow \text{N}_2\text{O}(\text{G})$	100	1.266 @ 185 K	+11.025 @ 185 K	+0.251 @ 185 K	0.509	100

\*A negative number indicates that the reaction is exothermic. A positive number indicates that heat input is required.  
Data derived from HSC.

The gas generant density number shown in the third column is valuable to calculate the cost of pressure shells required to house the gas generant during operation of a solid gas generator. The higher the density, the more compact the design of the gas generator (not counting the space occupied by the coolant bed and filters).

The energy release number shown in the fourth column indicates the exothermicity of the reaction. Some of the heat of reaction remains in the slag in the gas generator, and some of it is carried away with the hot gases. The gases from a pyrotechnic gas generator have to be cooled from the temperature at which they originate in the gas generator for several reasons:

- The hot gases might ignite prematurely if they are insufficiently cooled before oxidant and fuel meet in the mixing station.
- The fill time would be longer because of the lower density and higher viscosity of the gases.
- Less gas can be packed into the ram accelerator chamber before the projectile is fired into it.
- The elastomer gaskets in valves and diaphragm seals might get scorched by hot gases.

The coolant requirements to cool the gases to room temperature have to be calculated separately. There may also be a tradeoff between coolant requirements and accepting a slightly warmer gas (as long as it does not ignite).

Additional thermochemical calculations will calculate the gas generator combustion flame temperatures of gas generants currently under evaluation. For most other gas generator applications (airbags, oxygen candles), the gas is allowed to expand to atmospheric pressure, allowing the gas to cool. Very little expansion is expected as the gas flows from the gas generator into the ram accelerator chamber. There will be just sufficient pressure differential (maybe of the order of 68 bar = 1000 psid) to allow for rapid transfer of the gases. The pressure differential is a design parameter. The throttling orifice at the outlet of the gas generator determines the pressure differential and the gas fill rate.

The last column in Table 5 gives the gas formation in units of gas volume formed per mass unit of gas generant. This is an important evaluation criterion for evaluating different gas generants. For comparison, data for liquefied gases evaporated from cryogenic storage are included. The gas formation from liquefied gases is the most favorable number since no other chemicals are involved. Other logistic handicaps of cryogenic liquids (evaporative losses, mass of cryogenic storage vessels, heat required for rapid evaporation) are not included in this table.

Figure 4 shows the typical installation of a passenger-side airbag inflator in an automobile.

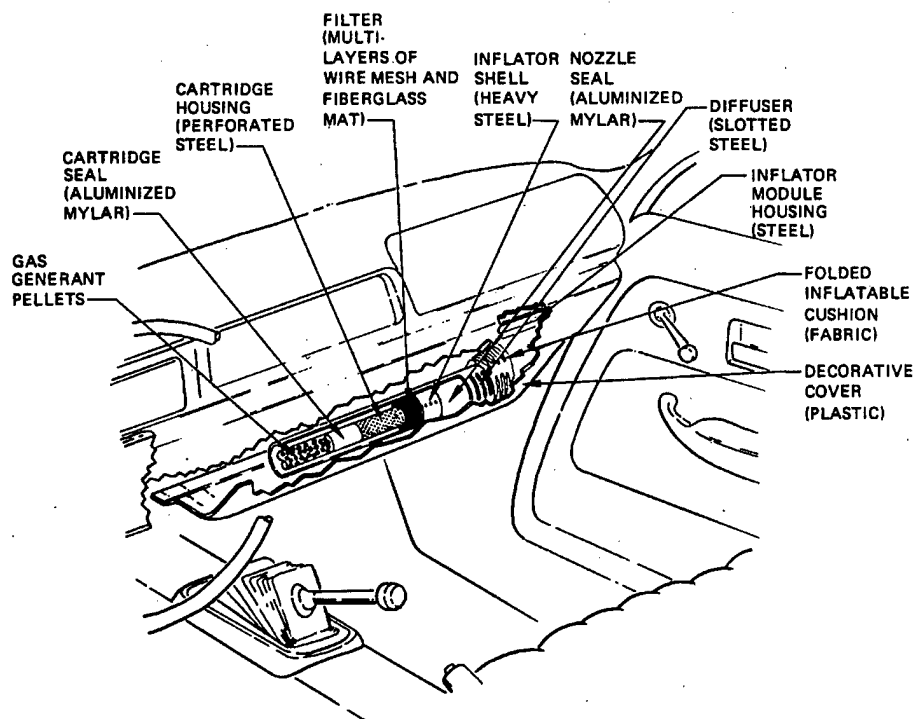


Fig. 2 — Cutaway view of inflator installed in automobile dashboard

Figure 4 Nitrogen gas generator for inflation of a passenger-side airbag installed in an automobile (from Schmidt 1980).

There are several hundred patents on sodium azide based gas generants, mostly for airbag applications, in which sodium azide is combined with various oxidizers and slag-forming additives. The author has maintained a data base on all airbag gas generants for several decades while actively involved in airbag inflators, but the data base has not been updated for several years. There is an even larger number of patents for nonazide gas generants which have come to replace the azide-based gas generants as a result of relaxing the carbon monoxide maximum tolerance in the exhaust gases. The nonazide gas generants are based on organic nitrogen-rich compounds such as 5-aminotetrazole, triaminoguanidinium nitrate, oxamide, azodicarbonamide and bitetrazole.

Slag-forming additives (clay, bentonite) facilitate the filtration of dust particles from the gas. Potassium nitrate, potassium perchlorate or other oxidizers are added to increase the burning rate of the azide compositions to above 50 mm/s (2 in./s). More recently, during the 1990s, most azide gas generants in new airbag inflators have been replaced by non-azide gas generants containing organic high-nitrogen compounds such as 5-aminotetrazole or triaminoguanidinium nitrate with potassium nitrate or ammonium nitrate as the oxidizer. These non-azide formulations have a small amount of steam, carbon dioxide and carbon monoxide in the exhaust, but the main exhaust constituent is still nitrogen gas. Again, there are several hundred patents describing non-azide gas generants for airbag applications. Non-azide gas generants are not very suitable for ram accelerator applications because of the water and carbon

dioxide content in the exhaust. It would be better to generate nitrogen from an azide-based gas generant and have dry nitrogen to pressurize the ram accelerator chamber.

The typical operating pressure of airbag inflators is 13.7 MPa (2000 psia.). Burn rate data exist only for very few gas generants for pressures up to 13.7 MPa (2000 psia.). We are currently attempting to gather industry data on the range of pressures for which burn rate data are available. The industry has so far had very little incentive to extend burn rate measurements to beyond 6.9 MPa (1000 psia) because none of the commercial applications required pressure data beyond this range. There was concern that in the range above 13.7 MPa (2000 psia.) the pressure exponent may become larger than 1.0, leading to progressive burn and eventually explosion of the gas generators.

There are numerous gas generator applications with solid gas generants where the chamber pressure is significantly above 3000 psia, for instance in explosively actuated devices (pyrovalves, ejection seats, cable cutters, munitions dispensing airbags). None of these use azide-based propellants. Operating pressures of some of these devices are up to 8000 psia.

It is interesting to note that the U. S. Navy has already looked at possible applications of commercial airbag-type gas generators for military ordnance applications. To quote from the abstract of one of these publications<sup>33</sup>:

*"Cost, reliability, and environmental considerations drive the Navy to consider commercial, off-the-shelf (COTS) pyrotechnic devices for some launch applications. In particular, this study examined the use of automotive safety restraint (airbag) initiators for the launch of some types of devices from submarines and surface ships. While low in energy, these inflators are manufactured to extremely high standards of reliability, are low in cost, are classified as pressure vessels, not explosives, and have no toxic combustion products. The tests and analyses performed in this study indicate that the automotive initiators are viable candidates for a wide variety of low-energy launch applications"*

In a follow-on effort, several commercial airbag gas generators were manifolded into one unit to meet the gas requirements of launching a device from a ship<sup>34</sup>. The interaction between bundled gas generators firing simultaneously or in sequence was analyzed. The same considerations can lead to the adoption of airbag gas generator technology to ram accelerators for U. S. Navy applications. While the abstract refers to "low-energy launch applications" (essentially throwing a sonar buoy device overboard), our combustion-enhanced application will put our proposed application more in the regime of a high energy launch application.

Another application proposed for nitrogen gas generators is as diluent gas generators for chemical lasers<sup>35, 36</sup>. These demonstration units contain up to 10 kg of gas generant and operate

<sup>33</sup> Silk, J., C. Trabert and J. L. Cipolla: Use of COTS gas generators in Navy Launcher Applications, NUWC, Newport, RI, CPIA-PUB-653-VOL-I, 33rd JANNAF Combustion Subcommittee Meeting, p.371-381 (Nov 1996)

<sup>34</sup> Williams, M. W., T. J. Gieseke and J. L. Cipolla: Physics-based Navy Launcher Model Using COTS Gas Generators, CPIA-PUB-662-VOL-I, 1997 JANNAF Combustion Subcommittee Meeting, 8 pp. (Oct 1997); CPIA PIRSU Y1998-05032

<sup>35</sup> Sauer, D. T., and A. H. Peterson: Solid Diluent for Chemical Lasers, Hercules, Inc., Magna, UT, RH-CR-84-9, Final Report, 83 pp. (Mar 1984) Contract No. DAAH01-82-C-0832

<sup>36</sup> Sauer, D. T., et al.: Solid Diluent for Chemical Lasers, Hercules, Inc., Magna, UT, CPIA Pub. 383 Vol. 2, 20th JANNAF Comb. Subc. Mtg., 347-354 (Oct 1983) Contract No. DAAH01-82-C-0832

at pressures of several thousand psi. Unfortunately, technical details from the laser gas generator developments are classified or limited and cannot yet be discussed at this place. It would be desirable to compile a classified addendum to the current study before the effort advances to the design and demonstration phase. It is quite possible that some of the laser gas generator hardware can be adapted to the ram accelerator application.

Another application for nitrogen gas generators was as a replacement for a helium compressed gas cylinder in gun-launched guided projectiles for a 155-mm gun. Various azide-based gas generants were evaluated for this application<sup>37, 38</sup>. One of the gas generants (UTG-FM-64) consisted of 63.75 sodium azide, 26.25% iron(III) oxide and 10% manganese(II) oxide. Tests were conducted with 37-mm (1.5-in.) diameter, 20-cm (8 in.) length end-burning grains operating at 8.2 MPa (1200 psi) chamber pressure for 37 s. Again, some of this technology can be applied to ram accelerators, in particular since it is also related to a gun application.

One consideration that needs to be kept in mind is the disposal of fired units and the demilitarization of unused units recalled from the field at the end of their useful life span. Because sodium azide is very toxic (similar to potassium cyanide, LD50 500 mg), special precautions are necessary for the safe disposal of these units in compliance with environmental protection laws. Unfortunately some of these common sense safeguards have been neglected when millions of azide-containing inflators were introduced as a life-saving device<sup>39</sup>.

Some passenger-side airbag inflators use a hybrid compressed gas/pyrotechnic gas generator technology, also called "prepressurized gas generator", where a pyrotechnic charge is mounted inside a high-pressure cylinder containing compressed gas. The firing of the gas generator hot exhaust against a burst disc weakens and ruptures the burst disc. The heat provided by the gas generator compensates for the adiabatic cooling during expansion of the compressed gas that would take place if the system consisted solely of a compressed gas cylinder. A typical airbag installation with a hybrid inflator is shown in Figure 5

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<sup>37</sup> Lawrence, W. J., J. C. Trowbridge and D. R. Matthews: Nitrogen Gas Generator Development - Cannon Launched Guided Projectile, UTC CSD Sunnyvale, CA, CSD-2559-FR, Final Report, 55 pp. (Oct 1975) AD-A019444

<sup>38</sup> Trowbridge, J. C., and R. O. MacLaren: Development of a High-Acceleration Resistant Gas Generation System, UTC CSD Sunnyvale, CA, CSD-2658-FR, Final Report, 47 pp. (Jun 1978) AD-A056751

<sup>39</sup> Schmidt, E. W.: Gas Generant Chemical Hazard Evaluation, SAE Paper 800295 (Feb 1980)

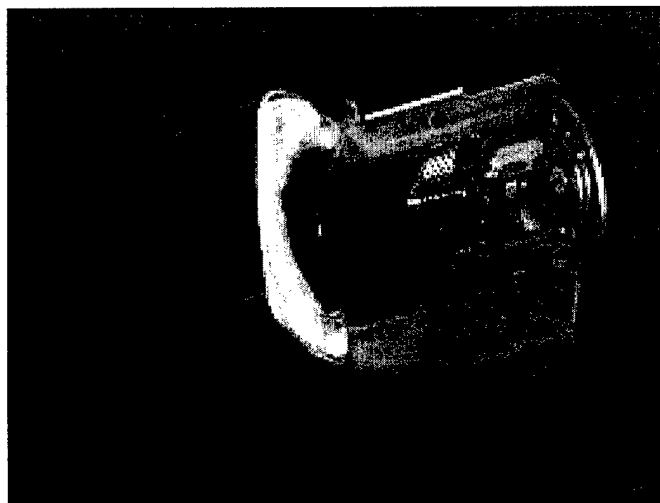


Figure 5 Cutaway View of Hybrid Airbag Inflator (Courtesy of Autoliv Inc.)

We can use a similar technique to generate gas mixtures of known compositions by firing an oxygen gas generator inside a compressed nitrogen tank or by firing a nitrogen gas generator inside an oxygen tank or by firing a nitrogen gas generator inside a methane, ethane or ethylene-filled tank, bringing the entire system up to full operating pressure. The word "hybrid gas generator" should not be confused with a hybrid rocket engine-type gas generator where a liquid or gaseous oxidizer is passed over a solid fuel grain.

### 3.5 Fuel Gas Generators

This section reviews possible gas generating reactions. The emphasis is on pyrotechnic solid gas generants, with liquid gas generants or hybrid/water reactive gas generants listed as alternate choices where solid gas generants are not available. Conventional chemical processing reactions, such as the steam reforming of hydrocarbons, are merely mentioned here but are not expected to meet requirements for rapidly sequenced filling of ram accelerators.

#### 3.5.1 Methane Gas Generators

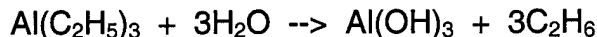
There are currently no known pyrotechnic solid-propellant gas generators that generate pure methane. Because methane lacks thermal stability, it would most likely decompose to carbon and other, higher hydrocarbons under the high temperature conditions of a pyrotechnic gas generator. If pure methane is needed in small quantities in the laboratory, it can be generated by the slow reaction of aluminum carbide (a solid) with water:



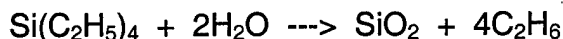
This reaction is similar to the reaction of calcium carbide with water. Operational aspects of water-reactive chemicals are discussed in a later section.

### 3.5.2 Ethane Gas Generators

There are currently no known pyrotechnic solid-propellant gas generators that generate pure ethane. Ethane is a hydrolysis product of many metalorganic compounds such as triethyl aluminum or diethylmagnesium:



An attractive source of ethane would be the hydrolysis of triethylsilane or tetraethylsilane. Unfortunately, this reaction does not occur at room temperature and requires higher temperatures to take place:

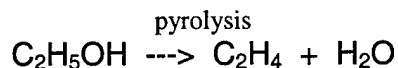


### 3.5.3 Ethylene Gas Generators

Ethylene is not readily generated from raw materials in the field. Ethylene crackers in petroleum refineries are major (multi-story) pieces of process equipment that are not readily scaled down. There are currently no known pyrotechnic solid-propellant gas generators that generate pure ethylene (also called ethene). For the more energetic and exothermic hydrolysis reactions, such as those of triethylaluminum, it is quite possible that under the conditions of the very hot reaction some of the ethane undergoes pyrolysis and converts to ethylene and hydrogen:



Industrial production of ethylene occurs in so-called ethane crackers where ethane or other alkanes are passed over heated surfaces. Small quantities of ethylene can be synthesized in the laboratory by dehydration of ethanol

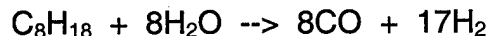


None of these reactions is suitable for rapid generation of ethylene to satisfy the requirements of ram accelerators.

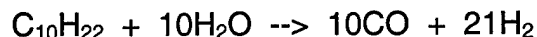
### 3.5.4 Hydrocarbon Fuel Gas Mixtures from Liquid Feedstocks

Hydrogen can be synthesized from hydrocarbon fuels readily available in the field (gasoline, diesel fuel, kerosene) by steam reforming:

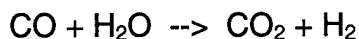
Gasoline (octane):



Diesel fuel (cetane, hexadecane):



The gas mixture of carbon monoxide and hydrogen is called "synthesis gas" because it is used for the synthesis of many other organic compounds in chemical industry (e.g., methanol, Fischer-Tropsch hydrocarbons, acetic acid). Additional hydrogen can be generated from synthesis gas by the shift reaction which can be pushed to completion if the carbon dioxide can be washed out and the product gas is recycled:



If the water is not condensed, then the water gas shift reaction is not pressure sensitive since the number of mols of gas on either side of the equation is the same. Steam reforming is an endothermic reaction and requires external energy input. In some cases the energy input can be provided by partial combustion of the hydrocarbon with oxygen. The by-products of steam reforming, carbon monoxide and methane must not necessarily be detrimental to the use of hydrocarbon-derived hydrogen in ram accelerators because they constitute ram accelerator fuels in their own right.

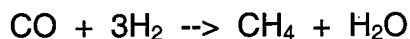
In addition to stationary steam reforming plants in ammonia and petrochemical manufacturing plants on a grand scale (megatons/day), there are several examples of steam reforming in mobile applications, such as in automobiles or, more recently, on airplanes.

For automobiles hydrogen has the lure of being a clean fuel. It can be used in internal combustion engines or in fuel cells. In internal combustion engines, hydrogen allows lean combustion because its range of flammability is so much wider than that of gasoline. Lean combustion generates fewer pollutant gases like carbon monoxide or nitrogen oxides. Hydrogen can be admixed to the normally used gasoline to allow the motor to operate in the fuel-lean instead of the fuel-rich regime<sup>40</sup>. This is called "hydrogen enrichment".

Instead of carrying a supply of water, water can be generated on board by partial combustion of hydrocarbon fuels, generating the correct ratio of hydrocarbon : water to complete the steam reforming reaction. There are numerous examples of partial combustion reactors.

For aircraft, steam reforming<sup>41</sup> has been considered as a means to use hydrocarbons for hypersonic combustion in hypersonic transports operating in the high atmosphere. Some of these airplanes plan on using endothermic reactions which can use some of the decomposing fuels to regeneratively cool the leading edge and other parts of the plane subjected to severe aerodynamic heating. For instance, methylcyclohexane decomposes to toluene and hydrogen. This fuel mix is suitable for hypersonic combustion in scramjets. Steam reforming would be another way to cool the leading edges and generate fuel suitable for hypersonic combustion at the same time, but the plane would have to carry water to do that. For ground-based applications, it is assumed that water would be readily available almost everywhere (except in desert climates).

Methanation of synthesis gas leads to methane



<sup>40</sup> Hoehn, F. W., and M. W. Dowdy: Hydrogen-Enriched Galoline for Autos, Automotive Engng. p. 52 - 56 (Nov 1974)

<sup>41</sup> Karpuk, M. (TDA Research, Inc., Wheat Ridge, CO): Steam Reforming, JANNAF 34<sup>th</sup> Combustion Mtg., CPIA Publ. \_\_\_\_ (1997)



This reaction is exothermic and is favored to the right by increasing the operating pressure. This process is carried out in large catalytic reactors and has been tested as the exothermic step in reversible reaction chemical heat pipes. It cannot readily be scaled down to a ship-board chemical synthesis plant. Long-range research on alternate logistic fuel supply methods for future large navy ships envisions separating carbon dioxide from atmospheric air and reducing it with hydrogen (from water electrolysis) to form a variety of hydrocarbon fuels. This fuel supply scheme depends on an abundant supply of electrical power (from on-board nuclear power plants).

### **3.5.5 Transition Metal Hydride and Carbon Nanotube Storage**

Only few fuels have sufficient energy content and a high enough sonic velocity to allow high-speed combustion in the last stage of the ram accelerator. Hydrogen is one of them. Although the current effort is aimed only at single-stage and first-stage accelerators, hydrogen fuel preparation is already included here in the anticipation of future multiple-stage ram accelerators.

Hydrogen can be stored with improved storage densities by reversible formation of metal hydrides of lanthanum/nickel or titanium/iron. These metals form nonstoichiometric hydrides in which hydrogen is adsorbed as interstitial compound into a crystal lattice of a host crystal. Metal hydride storage has been investigated extensively during the 70's in the wake of the oil embargo when work on alternative automotive fuels was at an all-time high.

Most recently, hydrogen storage in carbon nanotubes has been considered as an attractive means of hydrogen storage at low pressures and room temperature, approaching the storage density of liquid cryogenic hydrogen<sup>42</sup>.

### **3.6 Cryogenic Liquefied Gas Storage**

For all rocket applications, cryogenic storage of liquid oxygen and liquid hydrogen has been standard practice. Liquid oxygen is supplied to all advanced air force bases as breathing oxygen for pilots. As such liquid oxygen is not a newcomer to the logistics chain in the Air Force, but it is not commonly used in any U. S. Army application.

The problem with cryogenic liquid storage is boiloff during storage, even if vessels with superinsulation are used. An alternative to cryogenic liquid storage is supercritical storage. That would have the advantage that the gases are already at high pressure and less compressor work is required.

Cryogenic storage of fuels, oxidizers and diluents for ram accelerator or light gas gun applications is already being studied by other investigators and is not a subject of the current study.

### **3.7 Liquid Gas Generants**

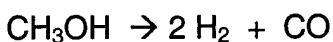
Although this approach deviates from the initial concept of using battlefield indigenous fuels, we are planning to include other liquid or solid fuels in this evaluation which are easily converted to ram accelerator propellant gases.

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<sup>42</sup> Rodriguez, N. M., and R. T. K. Baker: Storage of Hydrogen in Layered Nanostructures, U. S. Pat. 5,653,951 (5 May 1995/5 Aug 1997)

Liquid fuels which are easily decomposed generating hydrogen gas are methanol  $\text{CH}_3\text{OH}$ , ammonia  $\text{NH}_3$  and hydrazine  $\text{N}_2\text{H}_4$ . Some of the fuels listed have undesirable toxic properties compared to gasoline or diesel fuel. There would have to be compelling reasons to switch from a well-behaved fluid like gasoline or kerosene to a more toxic fuel. Nevertheless, an evaluation of the potential of these other liquids as hydrogen sources should be included in this study.

Methanol decomposes readily over a copper oxide / zinc oxide catalyst in reversal of its synthesis reaction to hydrogen and carbon monoxide:

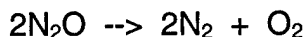


This reaction is endothermic and the energy required for thermal dissociation could come from combusting part of the methanol feed or burning the carbon monoxide after it has been separated from the hydrogen. The  $\text{CO}/\text{H}_2$  synthesis gas mixture is a potential fuel for ram accelerators.

### 3.7.1 Liquid Sources of Storable Oxygen

#### 3.7.1.1 Liquid Gas Generants for Production of Oxidants

Nitrous oxide can be used as an oxidant in ram accelerators either as such or after decomposition into its constituents, nitrogen and oxygen:

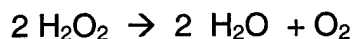


Nitrous oxide decomposition is already under consideration for space station atmosphere make-up<sup>43</sup>, for chemical lasers<sup>44</sup> and as a monopropellant<sup>45</sup>. Similar gas generators could be used to generate mixtures of nitrogen and oxygen at high pressures.

#### 3.7.1.2 Hydrogen Peroxide as a Source of Oxygen

Hydrogen peroxide is readily available as a 70% aqueous solution in tank car quantities. It is used in the bleaching of pulp and paper. Hydrogen peroxide used to be also available in higher concentrations (90%) in the U. S., but until recently the only sources for 90% hydrogen peroxide at this time were in Scandinavia.

Hydrogen peroxide decomposes when catalyzed by manganese oxide or samarium-oxide-promoted silver wire mesh:



This reaction is very exothermic (this is why high-test peroxide has been used as a rocket propellant) and will proceed at high pressures. One would have to use a heat exchange cooler

<sup>43</sup> Frankie B. M., S. E. Lowther and R. M. Zubrin: Nitrous Oxide Based Oxygen Supply System, Pioneer Inventions Inc., Patent WO9953983 (US Prior.23 Apr 1998/28 Oct 1999), also AU3753899; EP1077737 [<http://www.pioneerastro.com/NOBOSS/noboss.html>]

<sup>44</sup> Lewis, G. D.: Nitrous oxide decomposition reactor, United Technologies Corp., U.S. Pat.4002431 (19 Dec 1975/11 Jan 1977) Appl:US 75-64251, CA 86, 142083

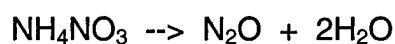
<sup>45</sup> Zakirov, V., Univ. of Surrey, Guildford, UK: Surrey Research Update on Nitrous Oxide Catalytic Decomposition for Space Applications, AIAA Paper 2001-3922

and condenser to remove the water before feeding the so generated oxygen to the ram accelerator. The U. S. Navy has a history of using hydrogen peroxide in steam generators for catapults for the launching of airplanes from aircraft carriers. After a hiatus of several decades, there is now renewed activity in the use of hydrogen peroxide as a "green" rocket propellant and high-test peroxide (HTP, >90% H<sub>2</sub>O<sub>2</sub>) has recently become available again in the U. S.

### 3.7.1.3 Solid and Liquid Sources of Nitrous Oxide

Nitrous oxide is a more energetic oxidizer than oxygen and could support ram accelerator combustion. It can be stored in the liquid state similar to carbon dioxide. It can be used in ram accelerator fill gases as such or it can be pre-decomposed to a mixture of nitrogen and oxygen and then mixed with a fuel.

Nitrous oxide can be generated by pyrolytic controlled slow decomposition of ammonium nitrate (a solid):



If the reaction is not carried out with careful thermal control, molten ammonium nitrate will explode (it has been the cause of numerous industrial accidents). It is not known if this reaction can be controlled so as to generate large quantities of nitrous oxide on short notice as in a gas generator feeding a ram accelerator. The separation from water formed in this reaction would involve an additional complication.

A mixture of oxygen and nitrous oxide can be generated by decomposition of hydroxylammonium nitrate (HAN):



Pure HAN is a solid, but is usually transported as a highly concentrated, 81% aqueous solution. HAN solutions with up to 96% HAN are viscous liquids at room temperature. HAN is the key ingredient to a liquid gun propellant called XM46 which was at one time considered for the U. S. Army's Advanced Field Artillery System (AFAS) gun. The U. S. Navy also tested HAN monopropellants as torpedo propellants (NOS-365). Both N<sub>2</sub>O sources above have to separate the N<sub>2</sub>O from the water that is formed as a by-product. The water will also contain traces of nitric acid. The decomposition of HAN into nitrous oxide, oxygen and water is exothermic and self-sustaining. It sometimes occurs prematurely during storage of highly concentrated HAN when the sample has been inadvertently contaminated ("fume off"). Cleanliness of storage tanks for HAN solutions is important. The author is currently involved in the development of high-temperature resistant catalysts for the decomposition of HAN as a rocket propellant.

### 3.7.2 Liquid Sources of Storable Hydrogen

One of the most effective methods to store hydrogen is in the form of hydrazine N<sub>2</sub>H<sub>4</sub>. Hydrazine decomposes on command as soon as it comes into contact with a catalyst:



This is the basis for application of hydrazine in monopropellant rocket engines and gas generators. Hydrazine monopropellant gas generators are in use in the F-16 fighter emergency power units and in the Space Shuttle auxiliary power units. Hydrazine gas generators are already in use in Germany for emergency deballasting of submarines and have been considered by the U. S. Navy for emergency deballasting of submarines. Hydrazine gas generator operation has been successfully demonstrated at deep-ocean pressures up to 55 MPa (8000 psia).

Dilute solutions of hydrazine hydrate are used in many ships to prevent corrosion in steam systems. There has been a reluctance on the part of the U. S Navy to allow any new uses involving hypergolic, toxic, liquid propellants on board of their ships for safety concerns.

Surprisingly, more hydrogen per unit volume can be stored in liquid hydrazine than in liquid hydrogen at cryogenic temperatures (compare data in Table 6).

Table 6 Storage Density for Hydrogen in Different Storage Media

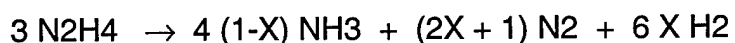
	Formula	Stored at, °C	Stored at, K	Wt% Hydrogen	Density, g/cm <sup>3</sup>	Stored hydrogen, g/cm <sup>3</sup>
HYDROGEN	H <sub>2</sub>	-253	20	100	0.0708	0.0708
AMMONIA	NH <sub>3</sub>	25	298	17.6	0.6819	0.1203
HYDRAZINE	N <sub>2</sub> H <sub>4</sub>	25	298	12.5	1.0037	0.1255

Ammonia dissociation is achieved quite readily over a wide range of catalysts:



This reaction is used in industry on a large scale to generate a reducing, protective atmosphere for processing (tempering, hardening, melting, casting) of steels and refractory alloys. The reaction is endothermic and requires external heating.

In contradistinction to the endothermic ammonia decomposition, hydrazine decomposition is exothermic and can generate nitrogen and hydrogen without consumption of external energy:



This reaction is in reversal of the theoretical formation of hydrazine from the elements, which would be an endothermic process (hydrazine is not manufactured from nitrogen and hydrogen but by a different route). The reaction can start spontaneously on iridium/alumina catalysts. Hydrazine decomposition gas generators are being used for submarine emergency deballasting where a high degree of ammonia dissociation (X) is desirable. The ammonia dissociation X in the above equation is a design variable and can be varied within a certain range by selecting the type of catalyst, the length of the catalyst bed, the dwell time, the flow rate, the temperature and the operating pressure. For the current application it would be desirable to maximize X. This is the same design goal as with underwater buoyancy generation.

### 3.8 Water-Reactive Chemicals as Gas Generants

Assuming that water is available in most U. S. Navy operations locations as a chemical reactant, it would be advantageous to have to carry only one of the reactants and consider water as "free" when calculating the effective hydrogen, oxygen or methane storage density.

A common disadvantage of water-reactive chemicals is that the reaction products are frequently insoluble in water. Thus, if a solid reactant/liquid water reaction is proceeding slowly, the reactive granule may become encapsulated with reaction product slag that impedes access of more water to the unreacted chemical and delays transport of reaction product gases to the surface. Instead of conducting the reaction in a stirred reactor, it may be better to conduct the reaction like a hybrid rocket where the momentum of the reaction products scours the surface of a solid grain and carries the reaction products away.

There are a number of liquid or solid water-reactive chemicals which can be used to generate fuel gases (Table 7).

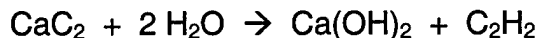
Table 7 Stoichiometry, Gas Formation and Heat Release of Gas Forming Reactions of Water-Reactive Chemicals

Equation	Reactant, mass%	Reactant Density, g/cm <sup>3</sup>	Heat Release*, kJ/FW @ 273 K	Heat Release, kJ/g, @ 273 K	Gas Release, L/g @STP**	Gas Output, mass% of gas generant**
<b>Fuel Gas Generants</b>						
$\text{Al}_4\text{C}_3 + 12\text{H}_2\text{O} \rightarrow 4\text{Al}(\text{OH})_3 + 3\text{CH}_4$	39.973	2.36	1676.56	4.656	0.467	33.43
$\text{CaC}_2 + 2\text{H}_2\text{O} \rightarrow \text{Ca}(\text{OH})_2 + \text{C}_2\text{H}_2$	64.017	2.22			0.350	26.00
<b>Oxidant Gas Generants</b>						
$2\text{KO}_2 + \text{H}_2\text{O}(\text{L}) \rightarrow 2\text{KOH} + 1.5\text{O}_2(\text{G})$	88.755	2.14	6.867	0.043	0.236	

\*A negative number indicates that the reaction is exothermic. A positive number indicates that heat input is required. Data derived from HSC.

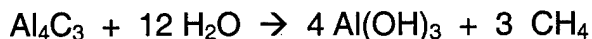
\*\* Not including mass of water. Water is assumed to be free.

The most commonly known water-reactive chemical is calcium carbide, which has been extensively used during the turn of the century (the 1899-1900 turn of the century, that is -- not the recent one) to generate acetylene for miner's lamps and for welding:



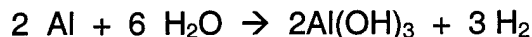
Acetylene has not been used in ram accelerators as far as we know. It has a very high positive enthalpy of formation, and it can autodecompose even in the absence of oxygen. Its detonation and combustion properties have been thoroughly evaluated. It should be evaluated as ram accelerator fuel in place of methane. There are undocumented reports that some antiquated gas cannons used mixtures of acetylene and air to propel projectiles. In many countries, air/acetylene noisemaker guns (open-ended, no projectiles fired) are installed in vineyards prior to the annual grape harvest to scare away the birds picking on the berries. The calcium carbide reaction with water and the generation of acetylene proceeds also at high pressures and the reaction is not shifted from right to left by high pressures. Confining calcium carbide and water in a European-style beer bottle with a snap closure, quickly closing the bottle and retreating to a safe distance to observe the explosion of the bottle has been a popular thrilling entertainment of budding, mischievous teenage chemists like the author in his younger years.

Not all carbides generate acetylene when reacted with water. Aluminum carbide will generate methane instead:



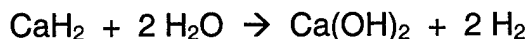
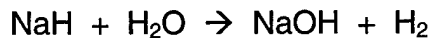
Methane is a preferred fuel for the first stage of ram accelerators.

Hydrogen can be easily and economically generated from aluminum metal shavings and water, catalyzed by a trace of mercury and alkali:



An aluminum-sodium alloy would sustain hydrogen evolution as long as there is unreacted water. The reaction of aluminum powder with water is being evaluated in ET-C gun propellants and for augmentation of underwater explosives.

A slightly more expensive source of hydrogen is the hydrolysis of alkali metal hydrides (lithium hydride, sodium hydride) or alkaline earth metal hydrides (calcium hydride):



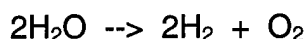
All these water-reactive chemical reactions proceed readily at pressures up to several thousand psi and will not depend on mechanical compressors to bring the gases to ram accelerator operating pressures. The water either has to be pumped at high pressure into a hydride-filled chamber (if one needs a repetitive operation device), or it can be packaged into a one-shot cartridge and hermetically sealed. The one-shot cartridge would consist of a reactor with compartmented reactants. When the dividing wall is ruptured, the reactants start mixing and high-pressure gas is formed. Means will have to be added to remove unreacted water from the gases so formed. This can be done by expendable desiccant cartridges containing chunks of lithium hydride or calcium hydride. Another method for removal of water vapor is to pass the

gases through a bed of molecular sieves or high-surface area alumina. These desiccant beds can be regenerated by heating and evacuating.

It is not known if the reaction between water and alkali peroxides and alkali superoxides is strong enough to generate oxygen at high pressures. One of the reactions considered is the reaction between potassium superoxide  $\text{KO}_2$  and water.

### 3.9 Electrolysis Gas Generators

Current submarines are assumed to use water electrolysis to generate oxygen for the atmosphere in submarines during extended periods of submerged operation. The International Space Station is testing a water electrolyzer as a means to maintain a breathable atmosphere. Similarly, oxygen and hydrogen as propellants for ram accelerators could be generated by electrolysis of water which should be in ample supply in a navy environment:



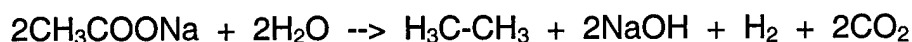
Unfortunately, this process cannot operate at very high pressure because the voltage required to achieve water electrolysis increases with the partial pressure at which the gases are generated:

$$E_p = E_1 + \frac{RT}{2F} \ln p$$

where  $E_p$  is the electrode potential at the pressure  $p$ ,  $E_1$  is the electrode potential at 1 atm,  $T$  is the absolute temperature and  $F$  is Faraday's constant.

The oxygen generated at the anode would be at the same pressure as the hydrogen generated at the cathode. This propellant production scheme would offer the ultimate logistic advantage in that all starting ingredients needed (water) are in abundant supply in a navy environment. Nitrogen needed as a diluent could be obtained by air liquefaction / fractionation or by reversible adsorption or membrane separation processes. The electrical energy needed for water electrolysis has to come from other on-board electrical generator facilities. Water electrolysis is being investigated for on-board propulsion of satellites with excess electric power. The maximum operating pressure demonstrated so far in electrolysis cells for satellite propulsion<sup>46</sup> is 1.38 MPa (200 psia). It has been claimed<sup>47</sup> that water electrolysis spacecraft using reversible fuel cells as electrical energy storage in place of batteries and using  $\text{O}_2/\text{H}_2$  for propulsion can operate at pressures as high as 13.8 MPa (2000 psia). This open-loop concept (as opposed to hermetically closed reversible fuel cells) is called *unitized regenerative fuel cell* (URFC). We should investigate the design changes required to operate electrolysis cells at higher pressure. The higher cell voltage does not appear to be a handicap as long as there is sufficient electric power on board of future navy ships using ram accelerator gun tube extensions.

Ethane can be synthesized by electrolysis of sodium acetate solutions:



<sup>46</sup> Campbell, J. G., and R. C. Stechman, Water electrolysis propulsion system testing, Marquardt, AFRL-TR-74-72, 208 pp. (Nov 1974), AD-A004886; PIRSU 1975-0035

<sup>47</sup> F. Mitlitsky, Applications of Water Refuelable Spacecraft, DARPA/TTO, January 5, 2000.

Ethane is formed by recombination of two methyl free radicals on the anode. It is not known if this reaction can be modified to produce ethane at high pressures, but this deserves more study. Separation of ethane from carbon dioxide has to be achieved by chemical absorption of carbon dioxide on caustic or by membrane separation. It would be desirable to operate the system without additional compressors. Hydrogen evolved at the cathode does not have to be discarded, but could possibly be added to enhance the fuel value of ethane so generated.

None of the electrolysis reactions can supply large quantities of gas in short time (order of seconds). They depend on diffusion of reactants from the electrolyte to the electrode surface and on diffusion of reaction products away from the electrode to avoid overvoltage complications. The electrolysis synthesis would require a plenum tank that would hold each of the gases between the ram accelerator actuations. It would take probably close to half an hour to bring a plenum tank back up to pressure by way of electrolysis without an additional compressor.

## 4 Other Considerations

### 4.1 Effect of High Pressure on Solid Gas Generant Burning Rates

The dependence of the burning rate of solid propellants and solid gas generants on operating pressure and initial gas generant temperature has been thoroughly studied for a wide range of propellants and gas generants. The burning rate of solid propellants and solid gas generants increases with pressure. The dependence is characterized by St. Roberts'/Vieille's law:

$$r = a p^n$$

where:

$r$  = linear burning rate, inch/second

$a$  = an empirical constant influenced by propellant temperature and geometry

$n$  = burning rate pressure exponent ("combustion index" - antiquated)

The same equation as above in logarithmic format is:

$$\log r = \log a + n \log p$$

If the data are displayed in a double-logarithmic graph, the function is a straight line and its slope is the burning rate coefficient  $n$  as illustrated in Figure 6. The burning rate coefficient is usually a small number between 0.05 and 0.5. If it approaches or even exceeds 1.0, there is imminent danger that the propellant combustion exceeds the ability of the nozzle to discharge the generated gases and the reaction chamber may explode. Burning rate measurements are often made with an end-burning sample in a constant pressure bomb (Crawford bomb), but very rarely at pressures exceeding 136 atm (2000 psia).

The burning rate coefficient for one type of sodium-azide based airbag inflator propellant was measured as 0.35. The burning rate of these gas generants at 136 atm (2000 psia) is between 25 and 50 mm/s (1 and 2 in./s), depending on propellant composition. For an azide-based gas generant with a theoretical flame temperature of 1273 K (1000°C), the burning rate at 136 atm



(2000 psia) is typically 37 mm/s (1.5 in./s). An extrapolation to higher pressures predicts that the burning rate at 200 atm will be 44 mm/s and at 400 atm it will be 56 mm/s.

### PRESSURE DEPENDENCE OF BURNING RATE St.ROBERTS' & VIEILLE's LAW

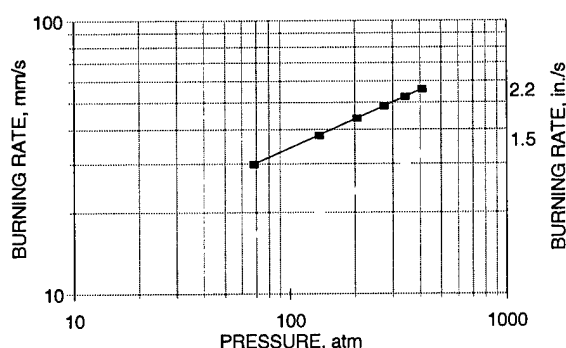


Figure 6 Pressure Dependence of Burning Rate of Azide-Based Gas Generant

Early versions of TRW (Hamill or Talley) passenger side airbag inflators were using steel shells and operated at pressures up to 33 MPa (4800 psia). Burning rate data obtained at TRW indicate that the pressure curve in this pressure range is still linear<sup>48</sup>. The gas generators use sixteen "hockey-puck" shaped pellets with one or more perforations ("donuts"). The pellets have a diameter of 41 mm (1 5/8 in.) and are 16 mm (5/8 in.) thick. The gas generant load of a passenger side inflator is approx. 450 g (1 lb). More recent designs use an aluminum shell and operate only at 13.7 MPa (2000 psia.). The aluminum shells have difficulty meeting the bonfire safety tests and may require an internal temperature-initiated ignition charge to activate them before the aluminum shell loses its structural integrity and leads to fragmentation or propulsive operation. Engineering test units of passenger-side inflators (without bags, no warranty for automobile application) are available for approximately \$150/gas generator.

Because azide-based inflators are being phased out, it may become difficult to find a commercial supplier for azide gas generants. In the wake of environmental and hazardous material disposal litigation, TRW is currently closing a Mesa, AZ production facility where most of the azide gas generant work was done during the past decade. The facility is being returned to its former owner (Talley Industries). TRW operates a production facility in Nevada that does mostly nonazide inflator work. Autoliv operates an azide gas generant production plant in Utah and is one of the few companies still making azide-based driver-side airbag inflators.

## 4.2 Thermochemical Equilibrium Calculations

Thermochemical equilibrium calculations in support of this project should be conducted to study:

- Effect of chamber pressure on theoretical combustion temperature
- Effect of chamber pressure on theoretical exhaust gas composition

<sup>48</sup> Personal communication, EWS to Dr. Harry Blomquist, TRW, Mesa, AZ (480) 722-6344

We have several computer programs available to perform more accurate thermochemical equilibrium calculations to obtain gas composition and temperature in the chambers and at the exit of the gas generators. For rocket applications, these programs are used to calculate Isp when expanding the gases in a supersonic nozzle. For our application, we would observe changes in temperature and composition as the gases are expanded from the gas generator operating pressure to the ram accelerator fill pressure. Heat sinks (coolant beds, filters) can be added to the program calculations.

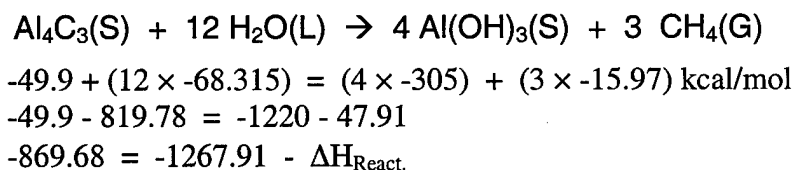
The programs available for this effort include HSC, NEWPEP, PEP2100, CETPC and CEA. We should also try to obtain a more recent version of BLAKE\_PC which accounts for real gas behavior at very high pressures. This program can also be used to study adiabatic heating for real gas conditions.

## 4.2.1 Exothermicity of Candidate Gas Generant Reactions

### 4.2.1.1 Exothermicity of Aluminum Carbide Hydrolysis Reaction

The hydrolysis of aluminum carbide is not well described in the literature. There appear to be only very few applications of this reaction up to this time. The heat release and the theoretical exhaust gas composition of the aluminum carbide hydrolysis was studied using fundamental thermodynamics and thermochemical equilibrium computer programs.

The theoretical heat release under standard conditions (101 kPa, 298 K) of the reaction



is

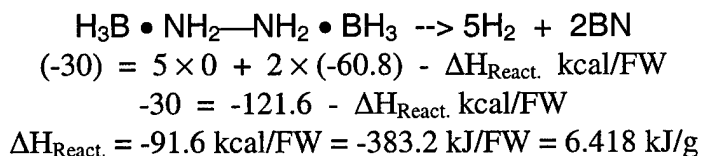
$$\Delta H_{\text{React.}} = -1267.91 + 869.68 = -398.23 \text{ kcal/formula weight (exothermic)}$$

$$\text{Formula weight: } 143.96 + 12 \times 18.015 = 360.14 \text{ g}$$

$$\text{Exothermicity} = -398.23/360.14 = 1.106 \text{ kcal/g} = 4.63 \text{ kJ/g}$$

### 4.2.1.2 Exothermicity of Hydrazine Diborane Pyrolysis Reaction

A candidate source of hydrogen is the pyrolysis of hydrazine diborane (a solid) to hydrogen and boron nitride:



$$\text{Formula weight: } 59.712$$

## 5 Evaluation of Competing Propellant Storage / Propellant Production Concepts

Table 8 is a summary of various propellant storage / production concepts with a listing of advantages and disadvantages.

Table 8 Advantages and Disadvantages of Propellant Storage Concepts

Source / Mechanism	Propellant Gases Provided	Advantage	Disadvantage
Steam reforming of diesel fuel	Hydrogen	Diesel fuel widely available	Slow startup time. Gas output is at relatively low pressure, need compressor.
Cryogenic liquid storage	All gases	Existing technology. Vaporizers can generate high pressure gas.	Boiloff losses during storage. Accumulation of explosive atmospheres from boiloff. Boiloff gases need to be flared off or otherwise neutralized. Difficult logistics.
Metal hydride storage	Hydrogen	Technology has been dormant for 20 years since interest in hydrogen automobiles has declined.	Heavy metal hydrides constitute ballast that needs to be carried around. Still dependent on hydrogen transporters.
Nanotube storage	Hydrogen (and potentially applicable to other gases)	Potentially good storage densities	Unproven technology
Water-reactive chemical gas generants	Hydrogen, oxygen, methane, acetylene	Can deliver gases at very high pressures. Water is an ubiquitous reactant.	Discontinuous process.
Solid gas generants	Hydrogen, nitrogen, oxygen	Very rapid gas generation rates. Can be combined in a cartridge that delivers gases in the correct ratio.	Potentially expensive ingredients. High transportation weights.

Evaluation criteria will be defined and given different weighting factors, depending on their importance. The various concepts will be evaluated against these evaluation criteria figures of merit will be derived. The figure of merit is the product of the individual rating of a candidate concept times the weighting factor. Adding all products for a given concept results in an overall figure of merit. The concept with the highest rating is then recommended for further experimental study.

It may also be possible to combine the propellant needs for the primary acceleration of the projectile (currently assumed to used conventional gun propellants) and the ram accelerator "afterburner" section. Thus, instead of using double-base gun propellants for the first acceleration, it has been proposed to use a combustion driven gun that uses the same propellants as the ram accelerator, except with less diluent. The combustion chamber for the combustion-driven gun would be very similar to a rocket engine. Another variant of the primary drive would use only a pyrotechnic hot hydrogen gas generator for a light gas gun, leading to higher injection velocities at the entrance to the ram accelerator section.

## **6 SUMMARY, CONCLUSIONS AND RECOMMENDATIONS**

### **6.1 SUMMARY**

In summary, we have identified a large number of candidate chemical reactions that can be employed in gas generators to produce the gases needed for operating ram accelerators at high pressure in various battlefield situations.

The sample case of filling a 20-cm I. D., 5 m long tube at 400 atm with a mixture of 3.9 kg methane, 16 kg oxygen and 51 kg nitrogen requires 11.66 kg aluminum carbide, 71.8 kg of a  $\text{NaClO}_3/\text{Fe}$  oxygen candle and 111 kg of an airbag-type nitrogen gas generant ( $\text{Fe}_2\text{O}_3/\text{NaN}_3$ ). Water needed for the aluminum carbide reaction is assumed to be free. These numbers are just for the consumables, they do not yet include the gas generator hardware, dust filters and any ducting. The three gas generant consumables add up to only 195 kg. This compares to the estimated 1000 kg (2000 lb) weight of a gun powder charge for the largest 406-mm (16-inch naval) guns that have been in use until 1990, capable of propelling 1900-2500-lb projectiles for over 30 miles. The masses to be stored and transported as part of the planned ram accelerator gas generator supply line are not much different from the masses that need to be moved for current technology 5-in. naval artillery guns or the U.S. Army's Crusader AFAS gun with a 155-mm (6 in.) howitzer.

### **6.2 CONCLUSIONS**

It is concluded that it is feasible to generate high-pressure gases needed for operation of ram accelerators by combustion of solid or liquid gas generants. The rate of gas generation could be fast enough to allow rapid refill between shots and allow repetition rates of several shots per minute.

There are numerous other applications of gas generators based on solid gas generants in the automobile and aircraft industry which provide a good foundation on which to base a gas generator evaluation program for the ram accelerator. This is an example of dual-use technology.

### **6.3 RECOMMENDATIONS**

The major shortcoming of the current study is that it does not contain engineering details of gas generators currently in production or produced for other applications in the past. It is recommended to conduct a survey of the pyrotechnic gas generator industry to obtain typical operating pressures, envelope and mass data of gas generators that are currently in production. Candidate companies to be contacted include General Dynamics Space Propulsion Division (former Rocket Research - Primex) in Redmond, WA, TRW Automotive Safety Systems in Mesa, AZ, Autoliv (former Thiokol) in Magna, UT, and Atlantic Research in Alexandria, VA. Companies may be reluctant to provide information unless we reveal our application. The companies are used to deal with inflator orders of several hundred thousand units and they may be reluctant to deal with a small research project customer like the University of Washington. We may have to exchange proprietary information agreements before we can proceed to the next phase of the program where we would acquire a gas generator and fire it into a ram accelerator tube section.

Single replacement airbag inflators (with airbags attached) are also available locally from airbag service companies, such as Airbag Service International LLC<sup>49</sup>. A complete 1999 Ford Taurus passenger side airbag unit (an azide unit made by TRW) retails for \$656 and we could negotiate a discount for returning the unused inflatable bags. There is a gray market for salvaged units (without warranty) that sell for about half the price of new units. However, if we decide to start using salvaged (most likely discontinued, no longer in production) units, the future supply is uncertain and the supply may dry out before we complete our test series.

As an alternate method of procurement, ONR could contract directly with one of the inflator suppliers and procure the gas generator(s) for the University of Washington. We should try and find out where the other Navy team obtained their inflators from when they tested them for the "soft" launching of sonobuoys and other devices from ships<sup>50</sup>. Feasibly we could use the same inflators from the same airbag supplier who provided the inflators for the other Navy team.

Initially, we could combine a pyrotechnic nitrogen gas generator with conventional methods of fuel and oxidizer gas mixing. If we perform demonstration firings with nitrogen gas generators at the UW, we shall have to conduct a safety evaluation beforehand and obtain approval from the cognizant UW safety committee. We shall have to show that the chamber in which we fire the gas generators is sturdy enough to withstand even a catastrophic failure of the gas generator inside. A thermal analysis will have to be conducted to make sure that heat released during the firing and heat soaking back later from the fired unit into the pressure shell will not weaken the pressure shell to the point of failure. For laboratory tests, the pressure vessel could be actively cooled externally to prevent overheating.

Another safety concern is the storage of the new gas generators prior to use in the ram accelerator. We may have to store them in a remote magazine licensed for the storage of explosives by the State of Washington. This appears to be an unnecessary precaution if one considers that almost every car nowadays has several airbag inflators in immediate vicinity of automobile occupants. However, we may be using inflator cartridges without the external filter and pressure housing of an inflator and once the cartridges are taken out of the inflator, they become an explosive device. In addition, we have to make provision for disposal of the spent units as hazardous waste.

We envision that an inflator (after removal of the inflatable bag and the manifold) could be mounted for demonstration firings inside a pressure vessel with a flanged lid (similar to a pressure autoclave). The airbag inflator industry uses similar chambers with flanged lids to measure the pressure-time curves and total gas output of inflators. This is done routinely, initially as development tests or later as quality control tests with statistical evaluation of results. The pressure vessel used for our initial tests would have sufficient vacant volume to act as a buffer volume ("plenum chamber") between the gas generator and the tube section to be filled. This space is wasteful since it detracts from the gas that can be delivered to the ram accelerator tube. We envision that the plenum space can be reduced once we have gained sufficient experience in the firing of gas generators for this application. The airbag gas generators are too big to fit inside a 38-mm I. D. section of the ram accelerator itself.

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<sup>49</sup> Airbag Service International LLC, 9655 S. E. 36th St., Mercer Island, WA 98040; Tel. (206) 275-4105; Doug Hansen, President. Personal communication, EWS, 5 Dec 2001.

<sup>50</sup> Silk, J., C. Trabert and J. L. Cipolla: Use of COTS gas generators in Navy Launcher Applications, NUWC, Newport, RI, CPIA-PUB-653-VOL-I, 33rd JANNAF Combustion Subcommittee Meeting, p.371-381 (Nov 1996)

<sup>50</sup> Williams, M. W., T. J. Gieseke and J. L. Cipolla: Physics-based Navy Launcher Model Using COTS Gas Generators, CPIA-PUB-662-VOL-I, 1997 JANNAF Combustion Subcommittee Meeting, 8 pp. (Oct 1997); CPIA PIRSU Y1998-05032

Initially we would test commercially available inflator units with integral filters and pressure shells. The pressure vessel with the inflator gas generator mounted inside would replace the nitrogen compressed gas cylinders that are currently used as a source of nitrogen. For future designs, we envision lighter-weight inflator cartridges similar to gun cartridges and containing only gas generant, firing into a sturdy, stationary filter that can absorb the dust from more than one gas generator firing. The filters might have to be replaced only after every five or ten gas generator shots. We will have to establish tolerable particulate contamination levels in the delivered gas. The light-weight gas generator cartridges would be sturdy enough to withstand transportation and handling forces, but would not carry their own pressure shell or filter. The gas generator cartridges would be loaded into a breech similar to a conventional gun breech and fired into a filter and gas distribution system. The cartridge loading mechanism would be similar to that for the 5 in.-gun that accelerates the projectile into the ram accelerator, using conventional gun propellants. The gas generator cartridge loading mechanism could be a revolving 6-barrel cylinder with sequenced or simultaneous oxidizer, diluent, and fuel gas generators firing into a mixing mechanism. In this fashion, three cartridges are ready to be fired, while the other three stations are reloaded with fresh cartridges.

One of the key questions is the effect of the high gas temperatures at the moment of release from the gas generator on the loading efficiency in the ram accelerator tube. The other concern is the potential inadvertent ignition hazard if the gases are still too hot at the point where diluent, oxidizer and fuel gases are mixed. This hazard did not exist with compressed gas cylinders as the gas source.